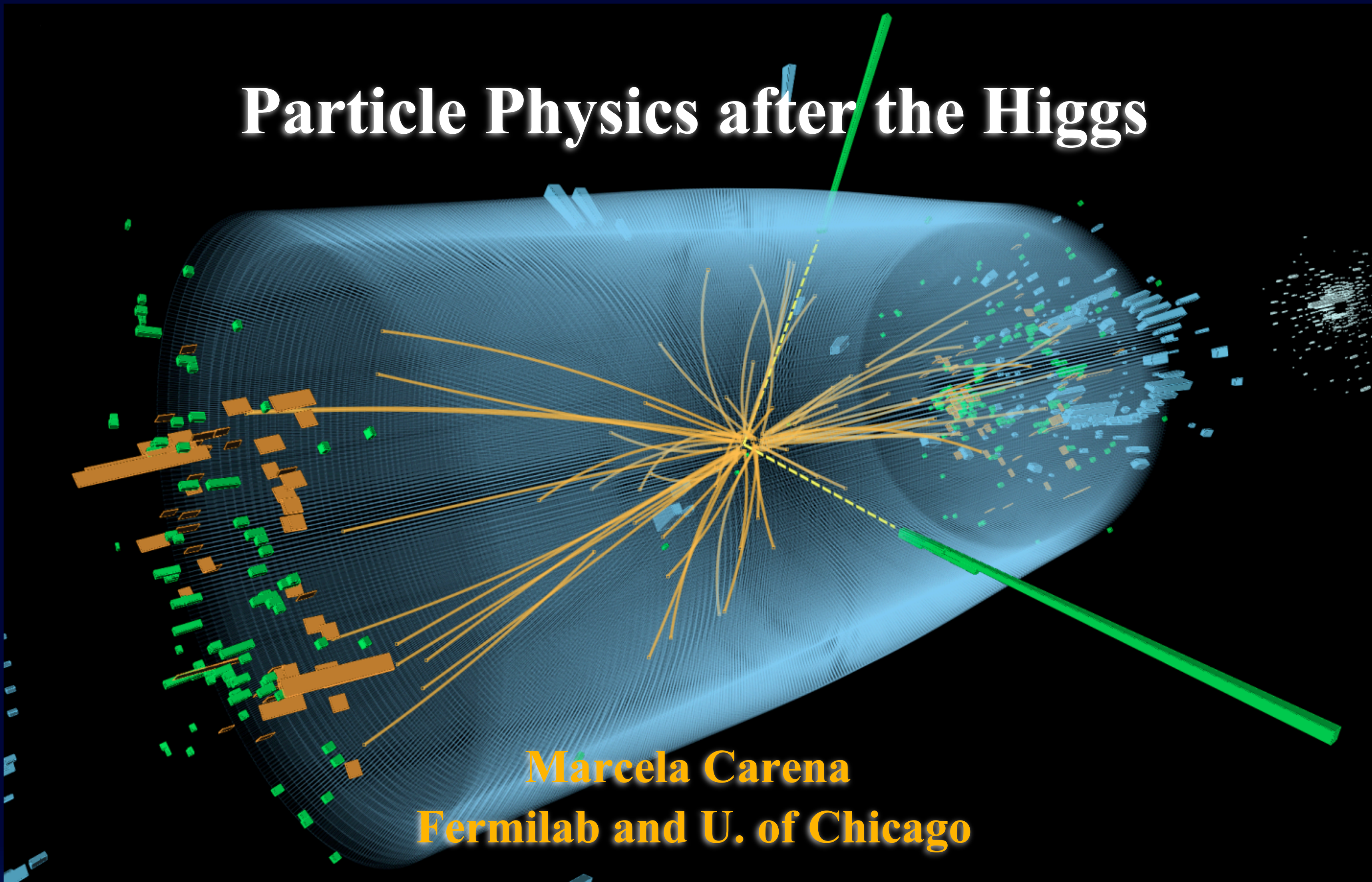
Particle Physics after the Higgs



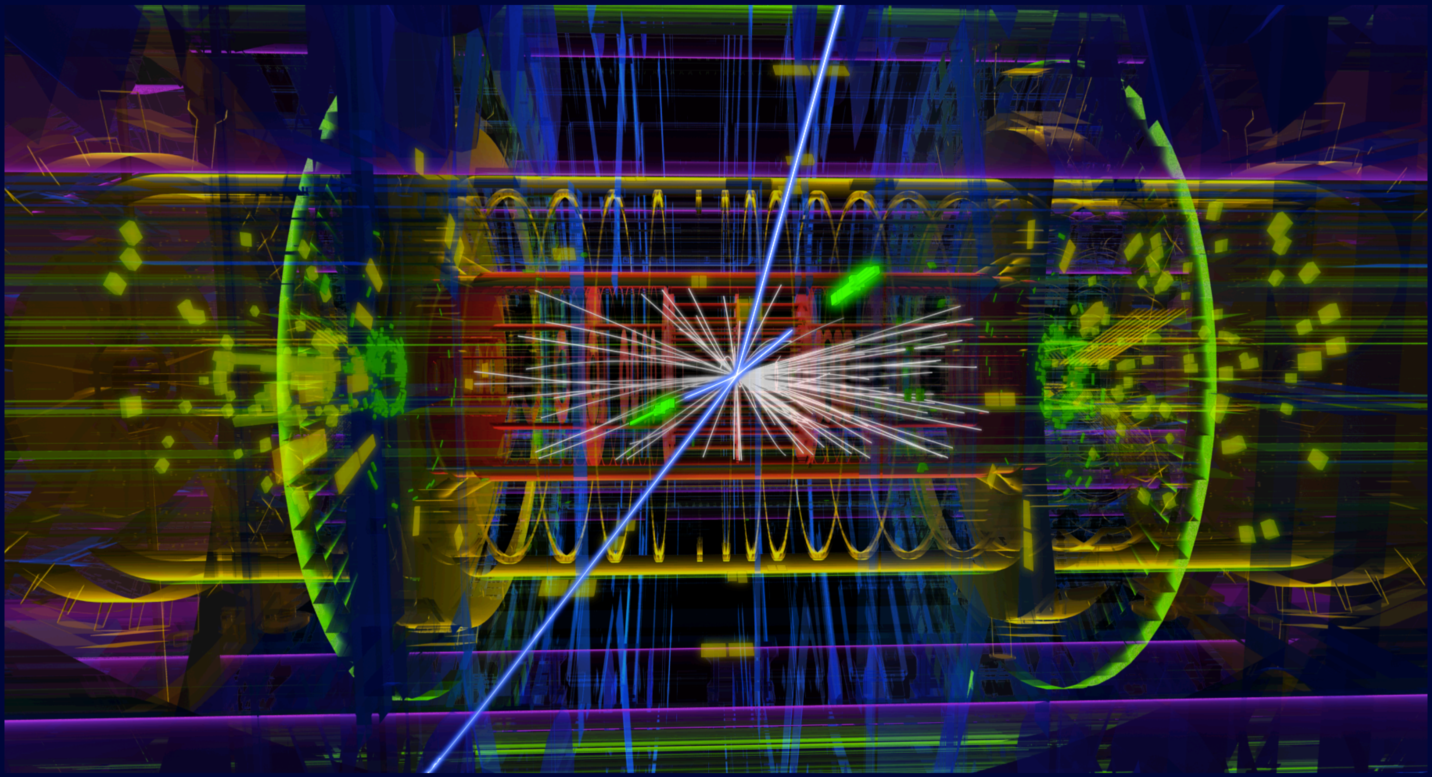
Marcela Carena

Fermilab and U. of Chicago

Harvard University Physics Colloquium

October 6, 2014

Fireworks on 4th July 2012

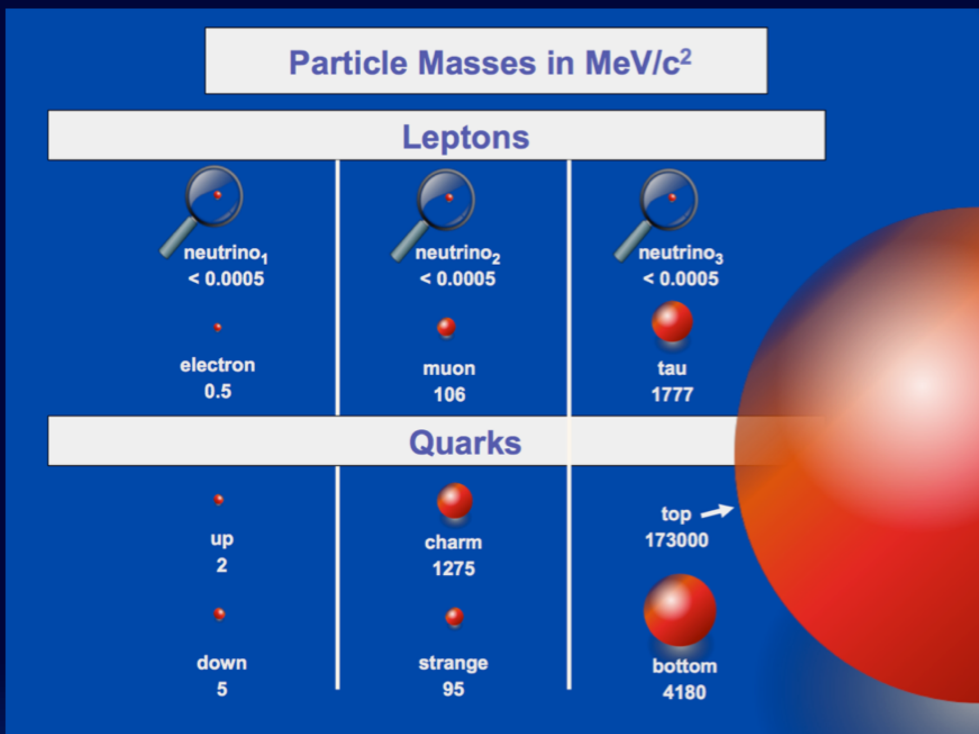


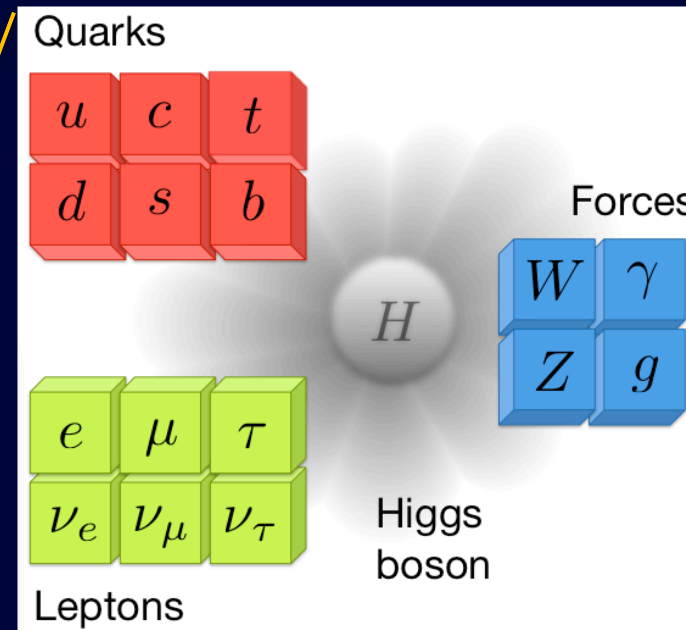
- Discovery of a new type of particle
- Discovery of a new type of force
- Start of a new era for particle physics at cosmology

The first time that the entire NYT Science section is devoted to a single story

Why is the Higgs so important ?

Sub-atomic particles of the
Standard Model of Particle Physics





They have all been produced in the laboratory

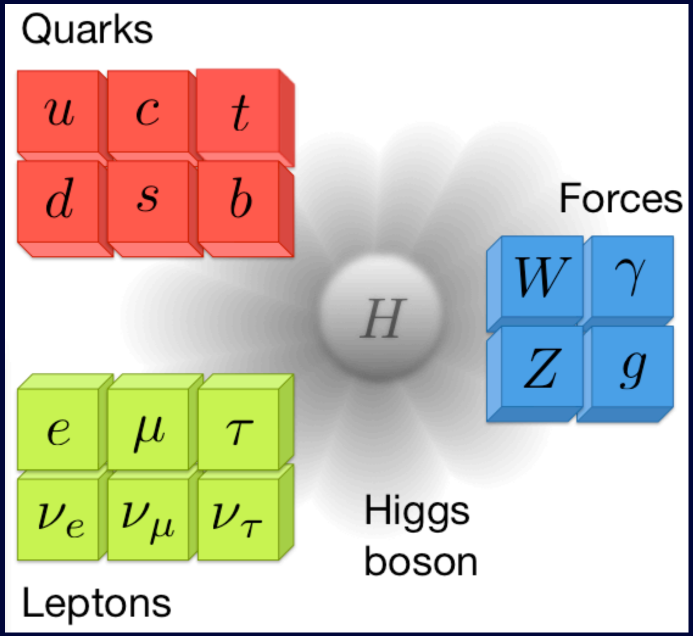
They have very different masses

What causes fundamental particles to have mass?

The Standard Model

A quantum field theory

- describes how all known fundamental particles interact via the strong, weak and electromagnetic forces
- has been tested with high precision at collider experiments



A gauge field theory

with a symmetry group

$$G = SU(3)_c \times SU(2)_L \times U(1)_Y$$

Matter Fields:

3 families of quarks and leptons with the same quantum numbers under the gauge groups

Force Carriers:

12 fundamental gauge fields

The Standard Model

Gauge Invariance:

- forbids mass terms for gauge bosons → $L = m^2 V_\mu V^\mu$
- allows to write mass terms for scalar and fermion fields

$$L = m^2 \phi^\dagger \phi \qquad L = m\bar{\psi}\psi = m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

only if L/R properties are the same

✓ Gluons and photons are massless

X Z and W bosons are massive

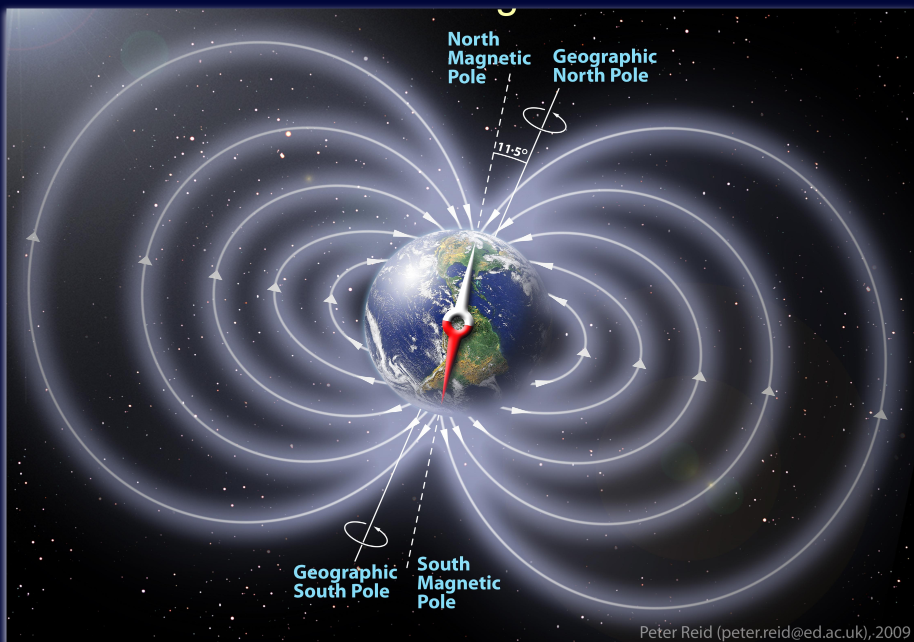
X Fermionic matter is massive, and the SM fermions are chiral

Weak gauge bosons and matter particles should be massless!
Clearly contradicts experience

What causes fundamental particles to have mass?

A field of Energy that permeates all of the space

Invisible Force Fields



The Earth's Magnetic Field

sourced by the Earth permeates nearby space

The Higgs Field

sourced by itself permeates the entire universe

What turns the Higgs field on?

Spontaneous Symmetry Breaking (SSB)

There is a symmetry of the system that is not respected by the ground state

Nambu (1960)

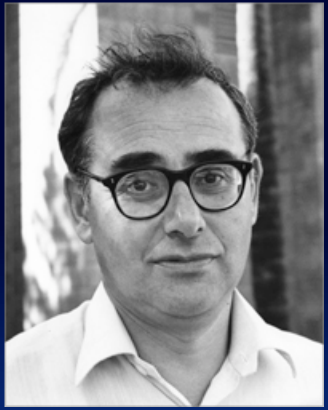
Nobel Lecture: Spontaneous symmetry breaking in particle physics: A case of cross fertilization*

Yoichiro Nambu

Physical system	Broken symmetry
Ferromagnets	Rotational invariance (with respect to spin)
Crystals	Translational and rotational invariance (modulo discrete values)
Superconductors	Local gauge invariance (particle number)

- **Apply condensed matter ideas to particle physics**

Now the quantum vacuum is the "medium"



Goldstone (1961)

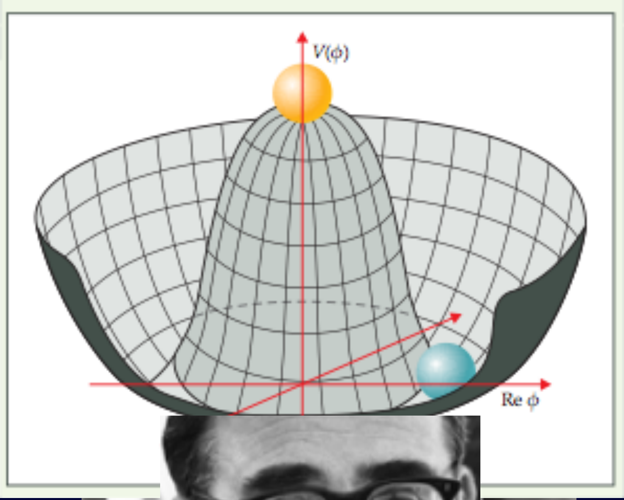
The Problem of the Massless Bosons:

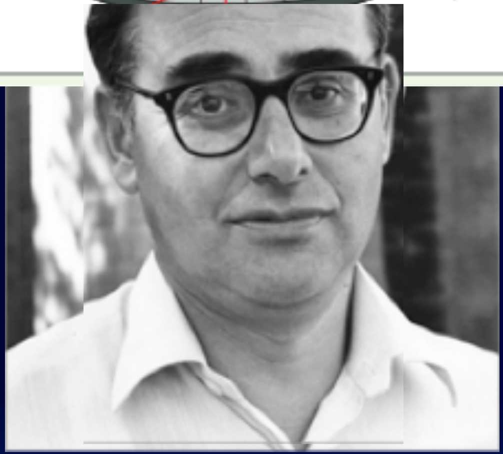
SSB implies a massless Goldstone boson per broken generator

What turns the Higgs field on?

Goldstone's Mexican Hat

$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$





- The Higgs field potential describes the energetics of turning on the Higgs field to a certain (complex) value
- The scalar field self-interactions may energetically favor a nonzero vev
- Because of the symmetry there are degenerate vacua

In quantum field theory it is difficult to transition from one degenerate ground state to another

"SSB is a property of large systems"

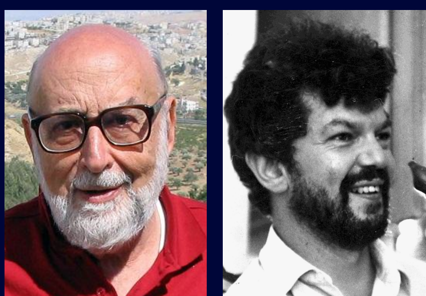
Anderson 1972

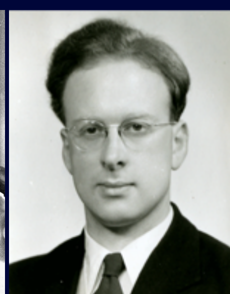
Still there are single particle excitations corresponding to locally deforming along the valley ➔ These are the massless Goldstone modes

Who invented the "Brout-Englert-Higgs" mechanism?

Nambu, Goldstone and Anderson penned important early chapters in the story of the Higgs Boson

"It is likely, then, considering the superconducting analog, that the way is now open for a degenerate-vacuum theory of the Nambu type without any difficulties involving either zero-mass Yang-Mills gauge bosons or zero-mass Goldstone bosons. These two types of bosons seem capable of 'canceling each other out' and leaving finite mass bosons only." **-- Phillip Anderson, 1962**





Englert Brout Higgs

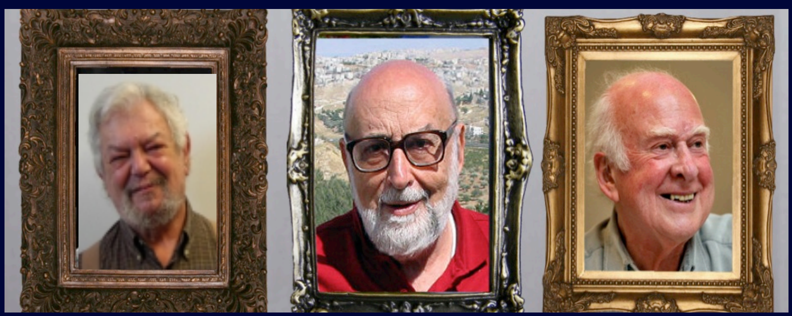
"The purpose of the present note is to report that...the spin-one quanta of some of the gauge fields acquire mass...This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson has drawn attention" **-- Peter Higgs, 1964**

" I couldn't have imagined 50 years ago, when I was working with my colleagues Gerald Guralnik and Tom Kibble on our paper, that society would spend billions of dollars and that thousands of scientists worldwide would be involved in the search for a particle and a mechanism that stem from those three papers published in 1964". **-- Carl Hagen, 2013**

Kibble Hagen Guralnik

The BEH + GHK Mechanism & the Higgs Boson (1964)

A fundamental scalar field with self-interactions
can cause spontaneous symmetry breaking in the vacuum,
respecting the sophisticated choreography of gauge symmetries,
and can give gauge bosons mass

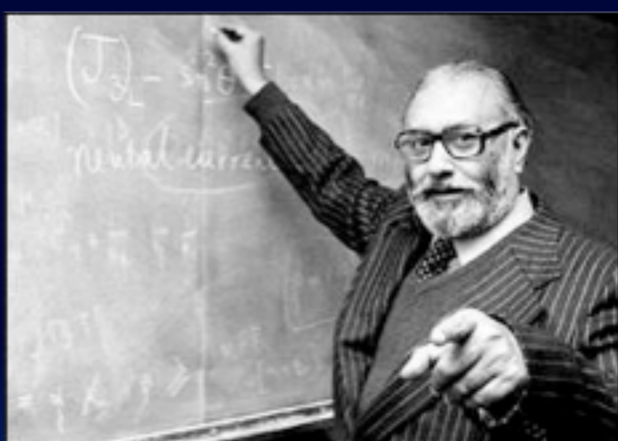


One particle left in the spectrum

Higgs explains: My first paper was rejected because it was not relevant for phenomenology

The Standard Model of Particle Physics

Weinberg-Salam: The electroweak SM (1967)



An $SU(2)_L \times U(1)_Y$ non-abelian gauge theory with chiral fermions

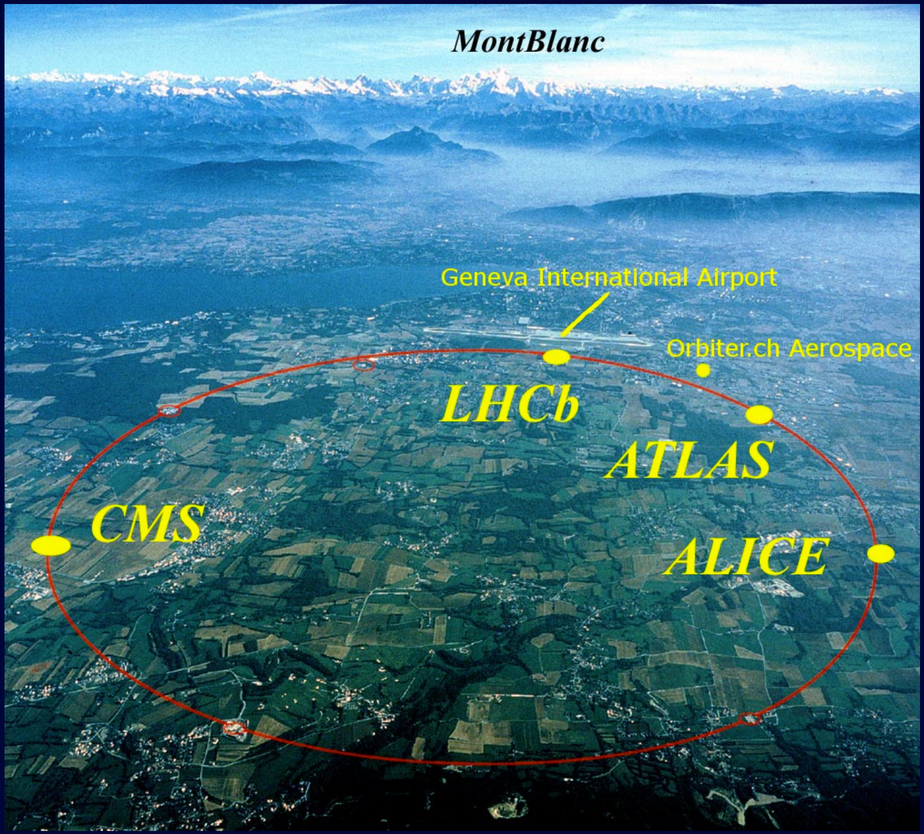
Spontaneously broken to $U(1)_{em}$ by a nonzero vacuum value of the Higgs field

Three of the four Higgs components (Goldstone bosons) are "eaten" to give mass to the W^+, W^-, and Z, leaving one neutral Higgs boson and a massless photon

The fermions also get mass from a new type of interactions (Yukawa int.) with the scalar field

Heavier particles interact more with the Higgs

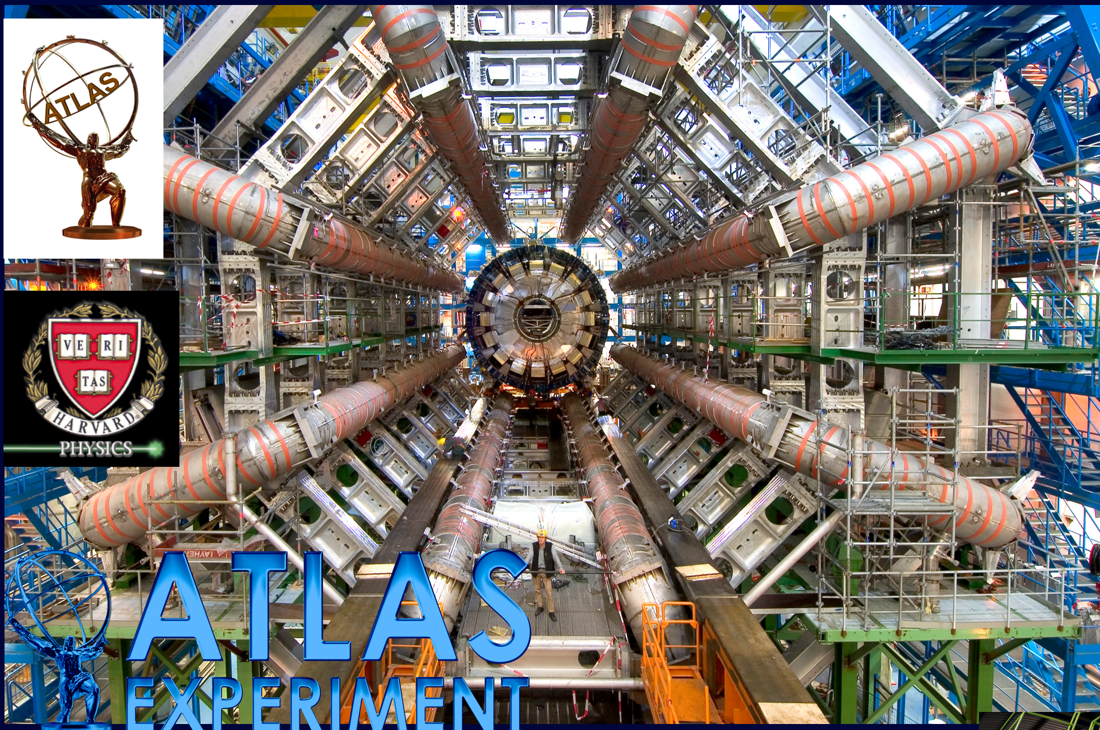
Half a century later: The Higgs boson discovery at the Large Hadron Collider (LHC)



proton-proton collisions
at E_{cm} = 8 TeV (13 TeV)

A 17 mile long vacuum pipe
300 ft below ground

To look at the new particles we have powerful detectors



Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500

Each experiment about

3000 physicists

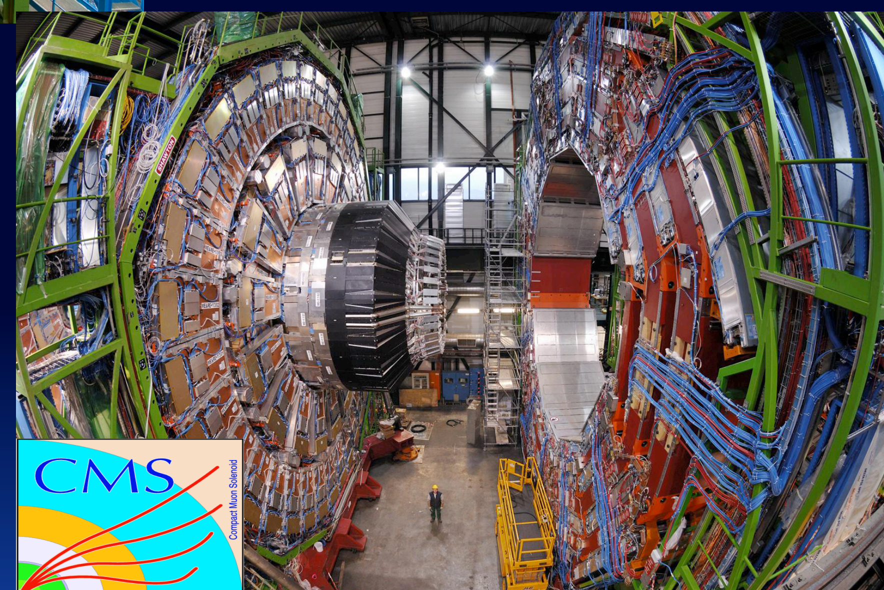
180 Institutes

40 countries

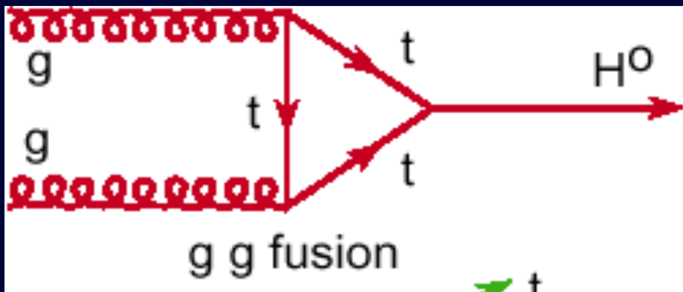
Huge, complex objects with cutting-edge technology that take "pictures" of collisions

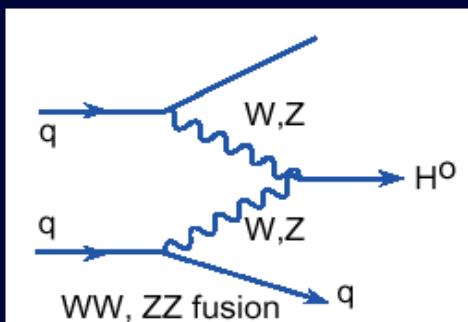
U.S. played a leading role in the Higgs discovery

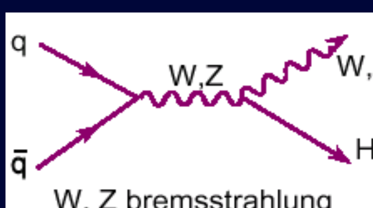
U.S. = 1/3 of CMS; U.S. = 1/5 of ATLAS

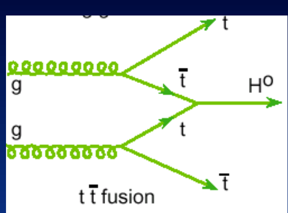


The SM Higgs at the LHC









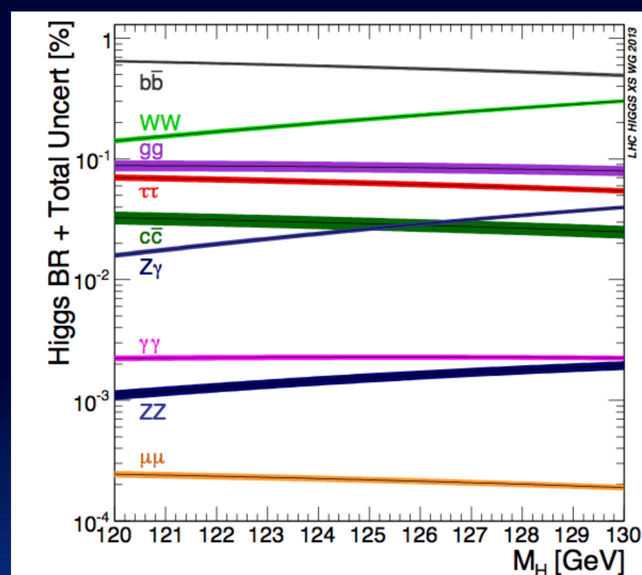
Higgs decays

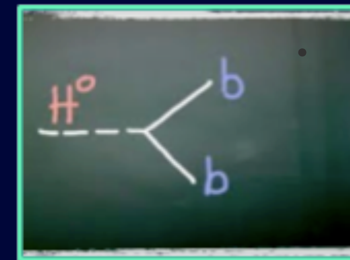
after about

100 yocktoseconds

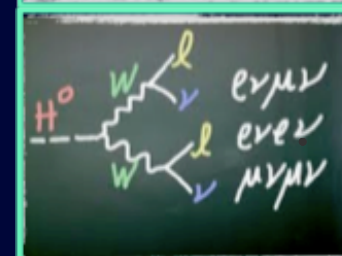
into various pairs

of lighter particles

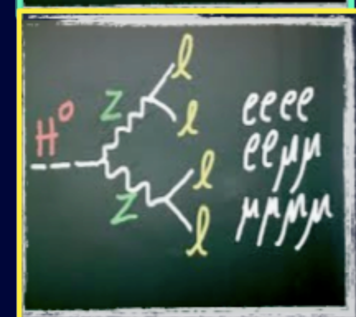




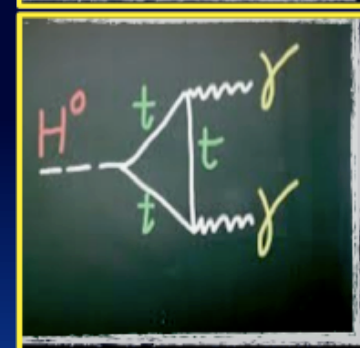
Lots of background



Neutrinos not detected



Rare but “Golden” channel



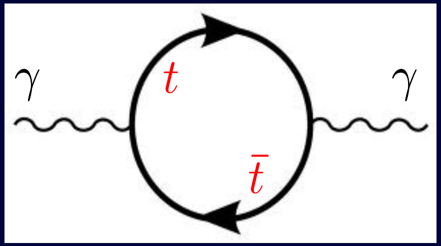
Rare but relatively clean

Quantum Fluctuations can produce the Higgs at the LHC

"Nothingness" is the most exciting medium in the cosmos!

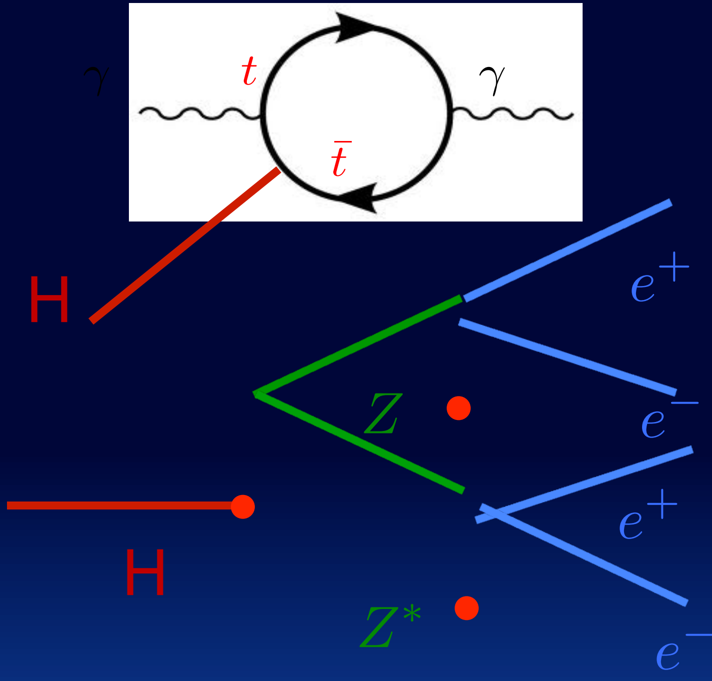
Photon propagates in Quantum Vacuum

Quantum fluctuations create and annihilate "virtual particles" in the vacuum

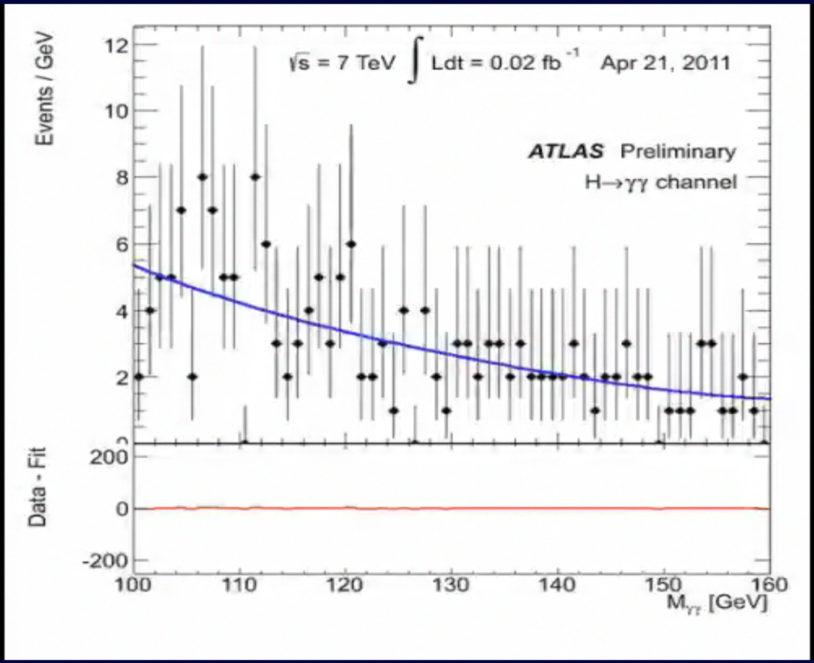


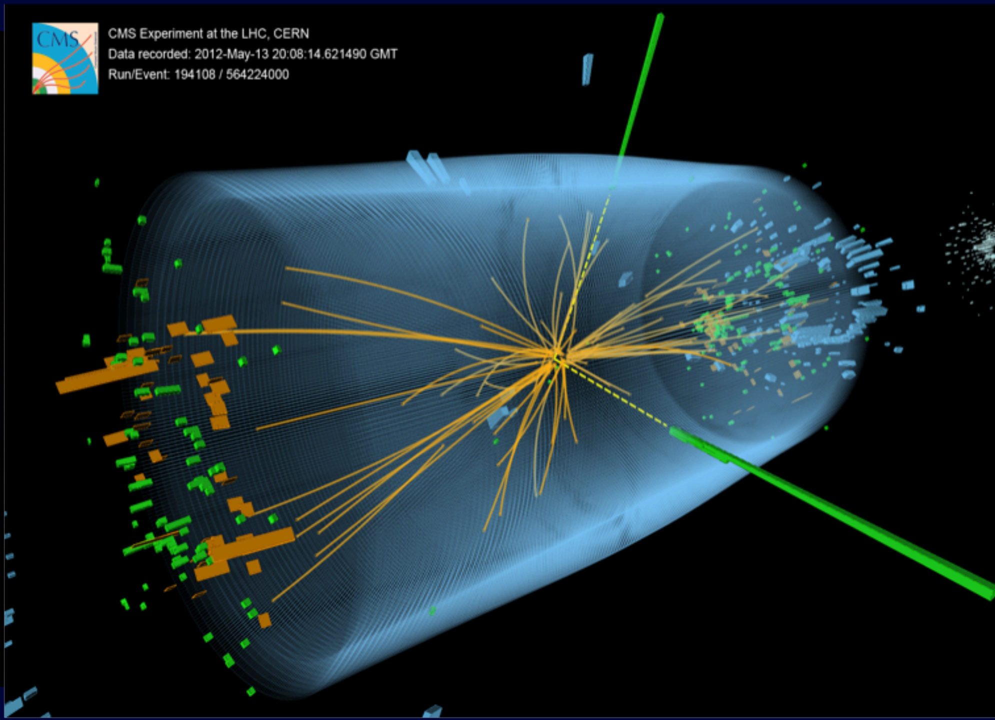
Higgs decays into 2 Photons

Higgs decay into 4 leptons via virtual Z bosons



The Discovery: Higgs ➔ two photons



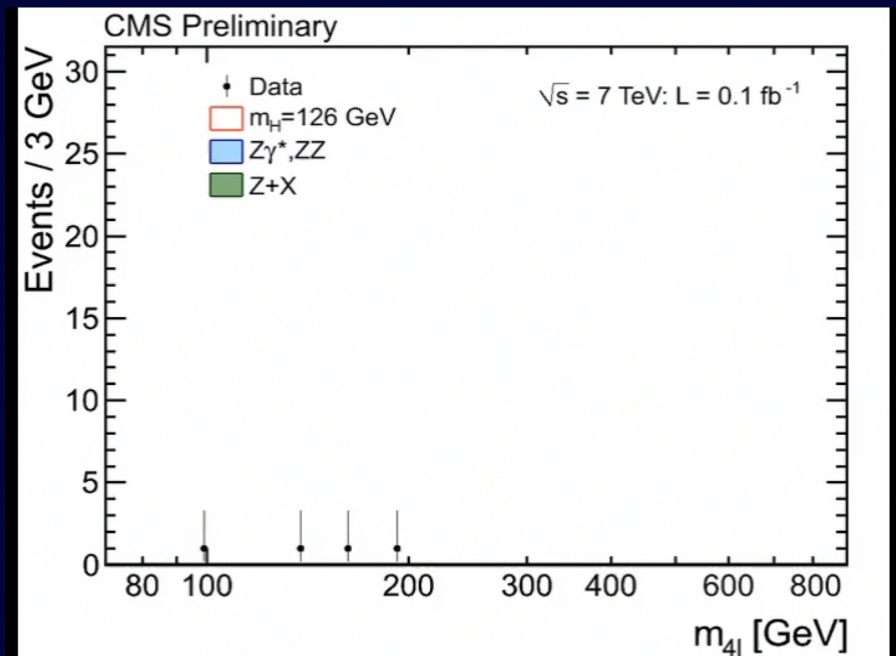


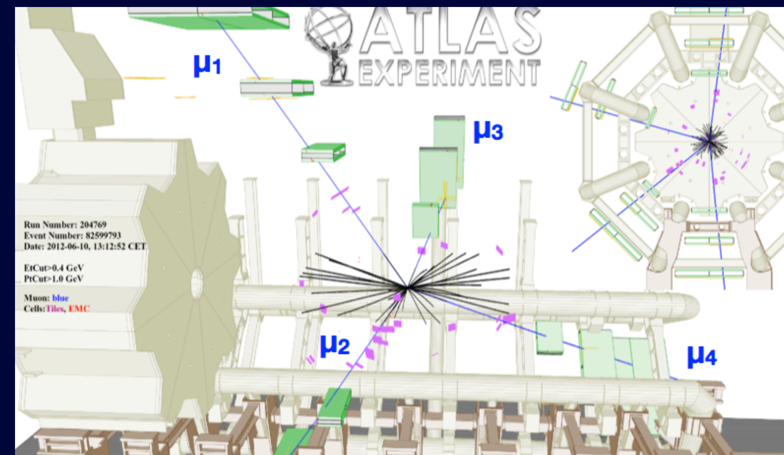
Search for a narrow mass peak with two isolated high E_T photons on a smoothly falling background

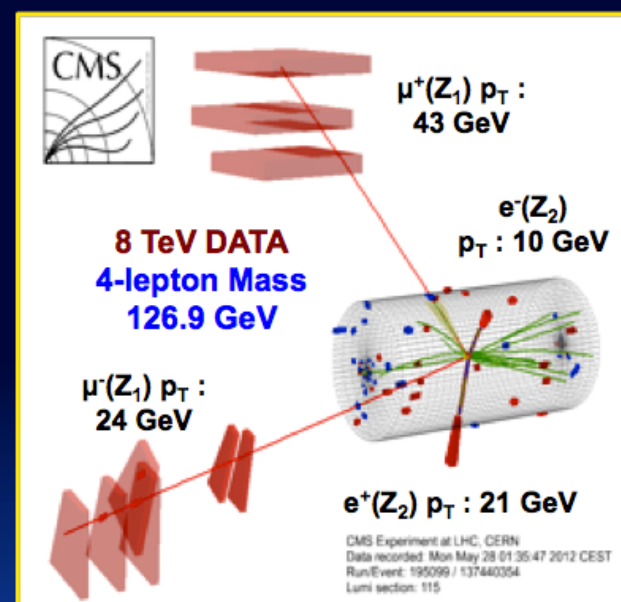
$$\mathbf{m_H} = [\mathbf{125.98 \pm 0.50}]\mathrm{GeV} \quad (\mathrm{ATLAS})$$

$$\mathbf{m_H} = [\mathbf{124.70 \pm 0.35}]\mathrm{GeV} \quad (\mathrm{CMS})$$

The Discovery: Higgs → 4 Leptons
with virtual Z bosons: The Golden Channel



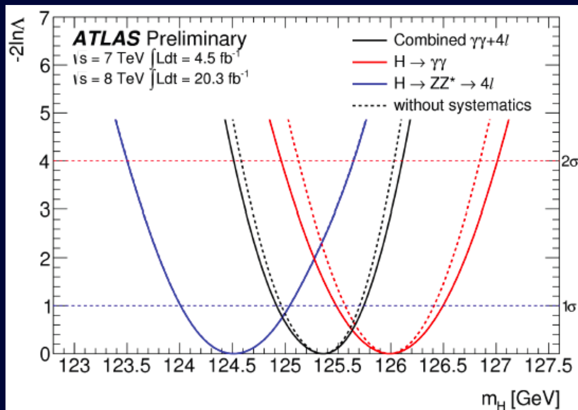




$$\mathbf{m_H} = [\mathbf{125.6 \pm 0.4 \pm 0.2}]\mathrm{GeV} \quad (\mathrm{CMS})$$

$$\mathbf{m_H} = [\mathbf{124.51 \pm 0.52}]\mathrm{GeV} \quad (\mathrm{ATLAS})$$

No doubt that a Higgs boson has been discovered

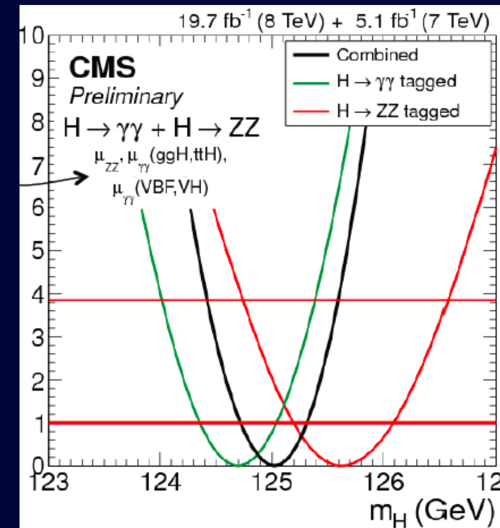


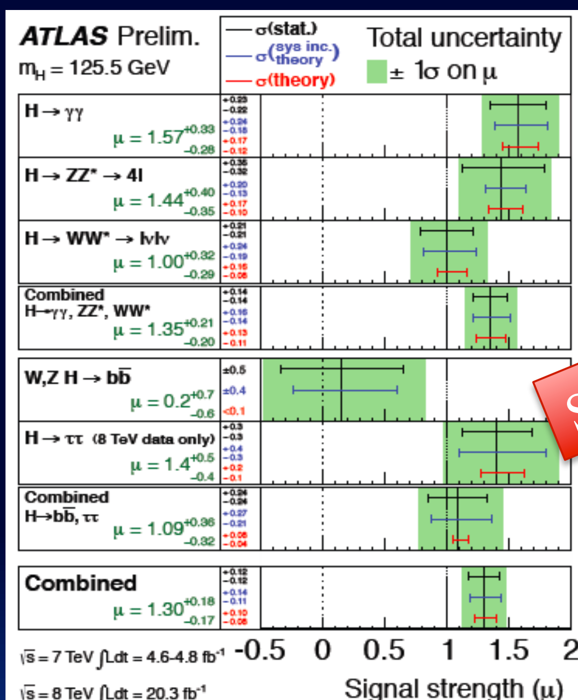
ATLAS:

$$m_H = [125.36 \pm 0.41]\,\mathrm{GeV}$$

CMS:

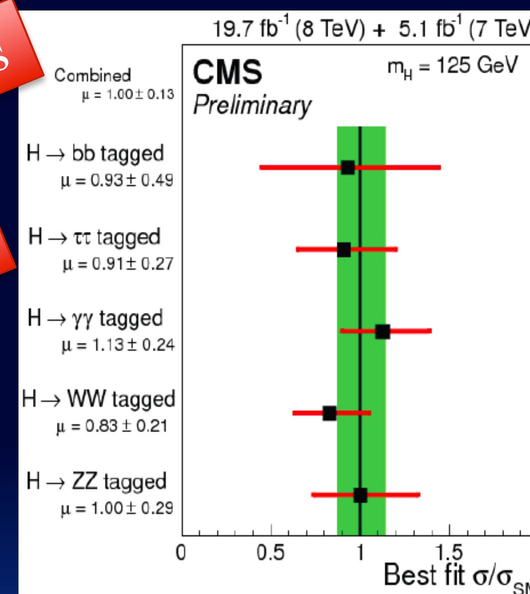
$$m_H = [125.03 \pm 0.03]\,\mathrm{GeV}$$





Signal compatible with SM Higgs

Also room for New Physics



$$\mu = 1.30 \pm 0.12\ (\mathrm{stat}) \pm 0.10\ (\mathrm{th}) \pm 0.09\ (\mathrm{syst})$$

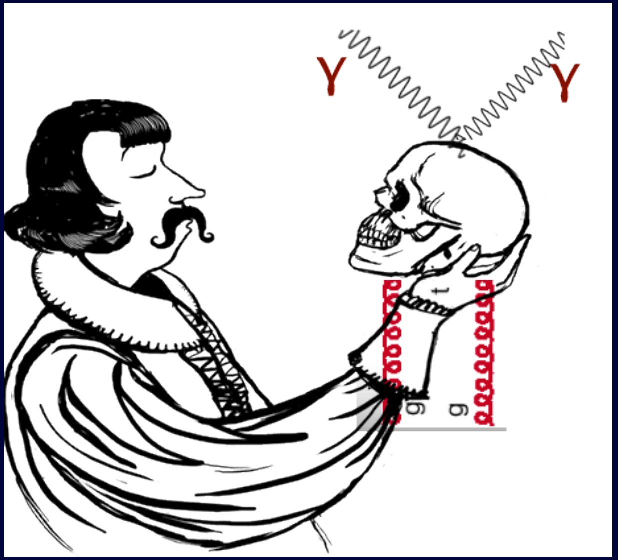
$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13\ \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

What kind of Higgs?

- Is it THE Higgs boson that explains the mass of fundamental particles?

  ~1% of all the visible mass

" The" Standard Model Scalar Boson, or not ....



- Is it just THE STANDARD MODEL HIGGS ?

• Spin 0

• Neutral CP even component of a complex $SU(2)_L$ doublet

• Couples to weak gauge bosons as

$$g_{WWH}/g_{ZZH} = m_W^2/m_Z^2$$

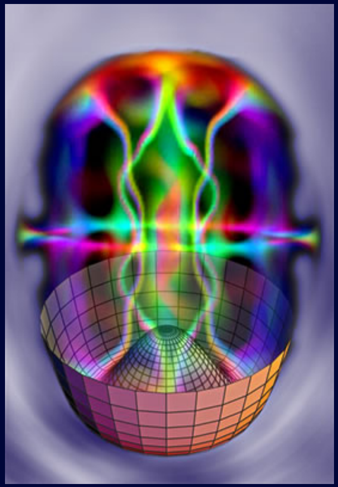
• Couplings to SM fermions proportional to their masses

• Self-coupling strength determines its mass (and v = 246 GeV)

- or just a close relative, or an impostor?

It could look SM-like but have some non-Standard properties and still partially do the job

- Could be a mixture of more than one Higgs
- Could be a mixture of CP even and CP odd states
- Could be a composite particle
- Could have enhanced/suppressed couplings to photons or gluons linked to the existence of new exotic charged or colored particles interacting with the Higgs



- Could decay to exotic particles, e.g. dark matter
- May not couple to matter particles proportional to their masses

The goal of the next LHC phase, staring in May 2015, is to answer these questions and search for new physics

Why to expect New Physics?

To explain dark matter, baryogenesis, dynamical origin of fermion properties.

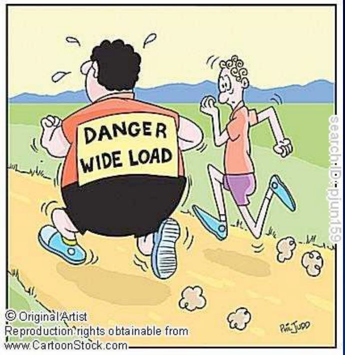
But none of the above demands NP at the electroweak scale

- **The Higgs restores the calculability power of the SM**
- **The Higgs is special : it is a scalar**

Scalar masses are not protected by gauge symmetries and at quantum level have quadratic sensitivity to the UV physics

$$\mathcal{L} \propto m^2|\phi|^2 \qquad\qquad \delta \mathbf{m^2} = \sum_{\mathbf{B,F}} \mathbf{g_{B,F}}(-\mathbf{1})^{\mathbf{2S}} \frac{\lambda^{\mathbf{2}}_{\mathbf{B,F}} \mathbf{m^2_{B,F}}}{\mathbf{32}\pi^{\mathbf{2}}} \log(\frac{\mathbf{Q^2}}{\mu^{\mathbf{2}}})$$

Although the SM with the Higgs is a consistent theory, light scalars like the Higgs cannot survive in the presence of heavy states at GUT/String/Planck scales



Fine tuning $\longleftrightarrow$ **Naturalness problem**

Two possible Solutions:

Supersymmetry (SUSY): a fermion-boson symmetry

The Higgs remains elementary but its mass is protected by the new fermion-boson symmetry

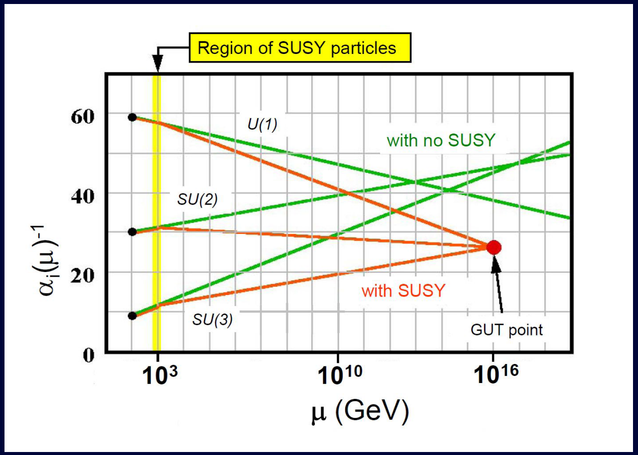
Composite Higgs Models:

The Higgs does not exist above a certain scale, at which new strong dynamics takes place

Both options imply changes in the Higgs phenomenology and New particles that *may* be seen at the LHC or indirectly in rare decay processes

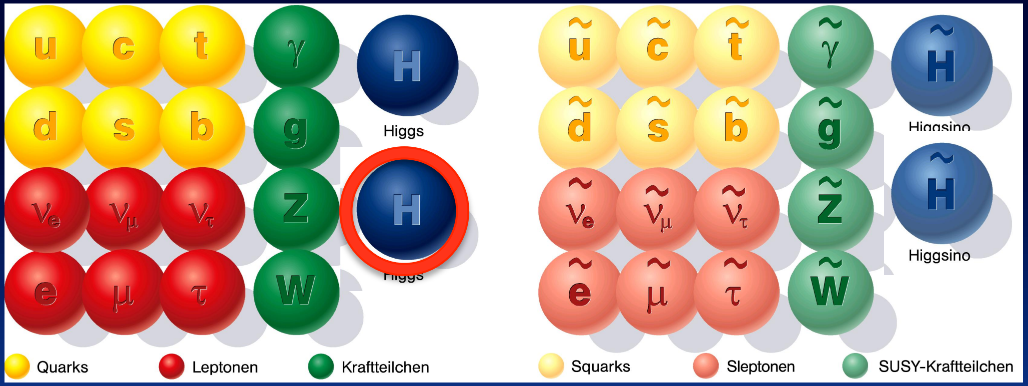
SUSY has many good properties

- **Allows a hierarchy between the electroweak scale and the Planck/unification scales**



- **Generates EWSB automatically from corrections to the Higgs potential**
- Allows gauge coupling unification at ~10^{16} GeV
- Provides a good dark matter candidate:

  The Lightest SUSY Particle (LSP)
- Allows the possibility of electroweak baryogenesis
- String friendly



For every fermion there is a boson with equal mass & couplings

Extended Higgs sector

SUSY and Naturalness

- Higgs mass parameter protected by the fermion-boson symmetry: $\delta \mathbf{m^2} = 0$

In practice, no SUSY particles seen yet → SUSY broken in nature:

$$\delta \mathbf{m^2} \propto \mathbf{M^2_{SUSY}}$$

If $M_{SUSY} \sim M_{weak}$ ⟶ Natural SUSY

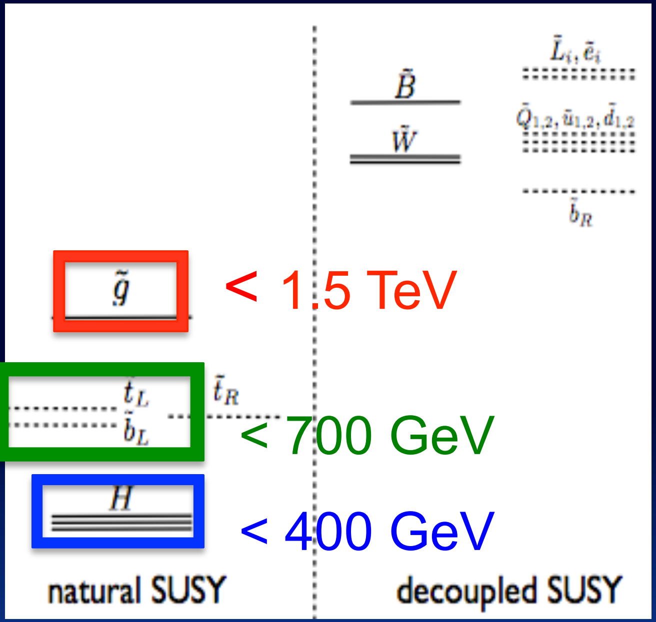
If $M_{SUSY} << M_{GUT}$ ⟶ big hierarchy problem solved

Where are the superpartners?

- **Not all SUSY particles play a role in the Higgs Naturalness issue**

Higgsinos, stops (sbottoms) and gluinos are special

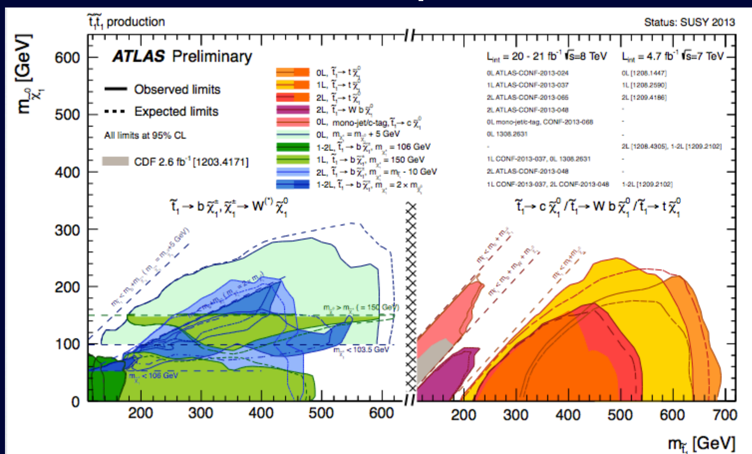
- So why didn't we discover SUSY already at LEP, Tevatron, or LHC8?



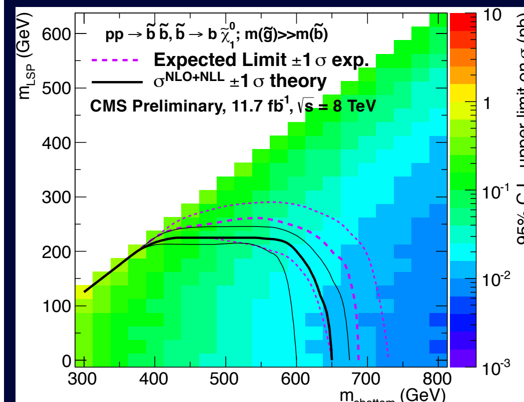
SUSY Weltschmerz*?

ATLAS/CMS are aggressively pursuing the signatures of "naturalness".

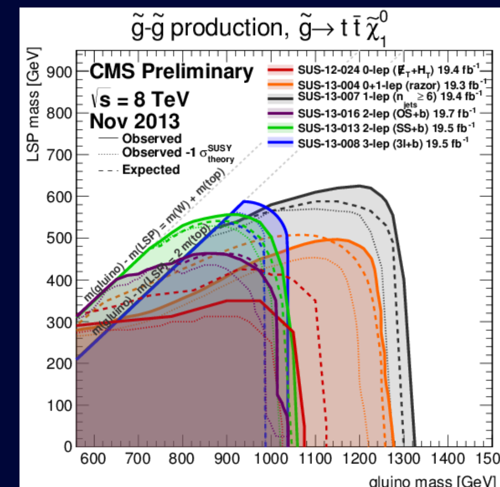
stops



sbottoms



gluinos



- **SUSY may be hiding and will show up in the new LHC run at 13 TeV**

-- Models with super-partners at kinematic reach of LHC8 but with the missing energy signatures or the jet activity degraded

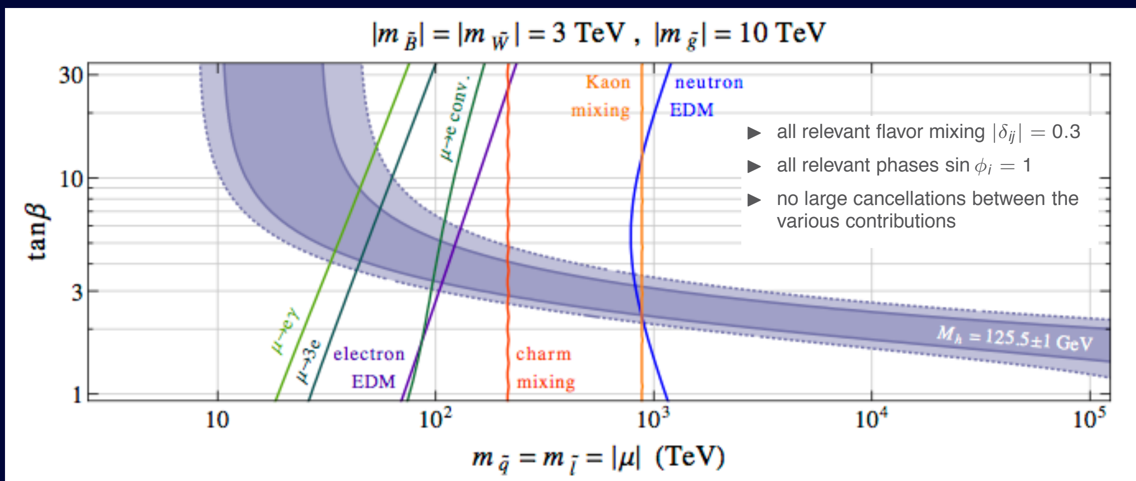
-- Non-minimal Natural SUSY models that lie in regions of parameter space unconstrained by LHC data; may address flavor and Higgs mass predictions as part of the SUSY breaking mechanism

**The feeling experienced by someone who understands that physical reality can never satisfy the demands of the mind*

SUSY may be at much higher energies?

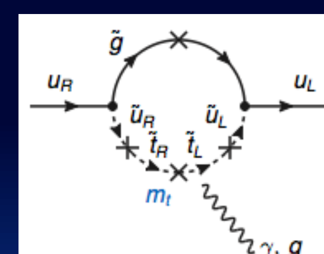
[Unnatural SUSY]

Low energy Probes of Flavor and CP violation with PeV Scale Sfermions



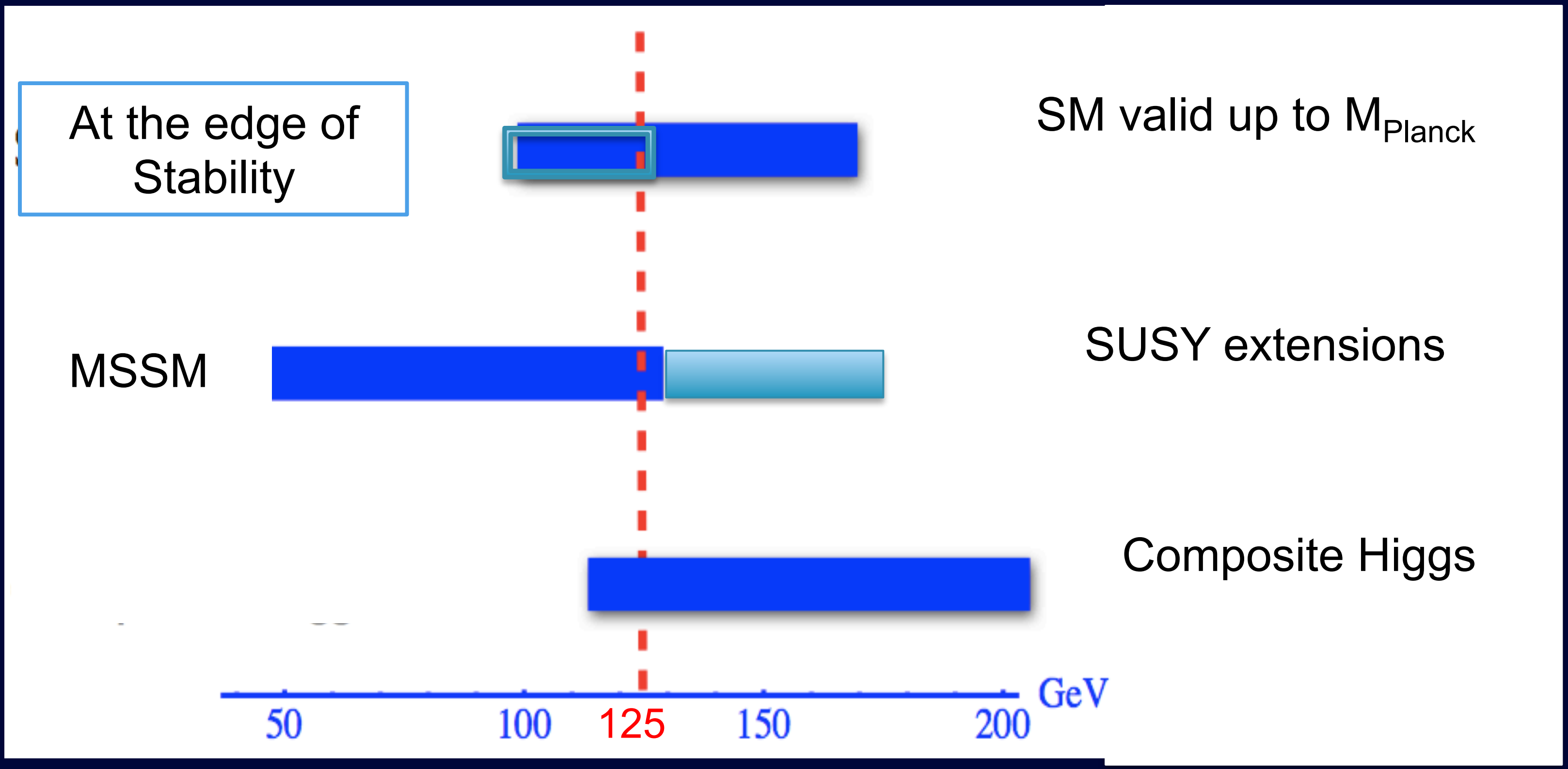
Heavy squarks, independent of the motivation, are good for the idea that flavor-violating effects may be intrinsically O(1), but with big mass suppression

- PeV squarks already probed by CP violation in Kaon mixing
- CP violation in charm mixing and the neutron EDM reach up to O(100 TeV)
- EDMs particularly interesting:



Not even a 100 TeV pp collider can probe this scales, so we need clues from rare processes

What does a 125 GeV Higgs tell us?



125 GeV is suspiciously light for a composite Higgs boson

but it is suspiciously heavy for minimal SUSY

What does a 125 GeV Higgs implies in SUSY?

SUSY also predicts *at least* four kinds of Higgs bosons, differing in their masses and other properties

Minimal SUSY :

2 CP-even Higgs: h and H with mixing angle α

1 CP-odd Higgs A and 1 charged Higgs H^{+-}

$$\tan\beta = v_2/v_1$$

$$v = \sqrt{(v_1^2 + v_2^2)}$$

Quartic couplings given in terms of gauge couplings, hence lightest Higgs mass m_h naturally linked to Z boson mass

$$m_h^2 \leq \underbrace{M_Z^2}_{< (91\text{ GeV})^2} \cos^2 2\beta + \Delta m_h^2$$

Important radiative corrections with strong dependence on top/stop sector

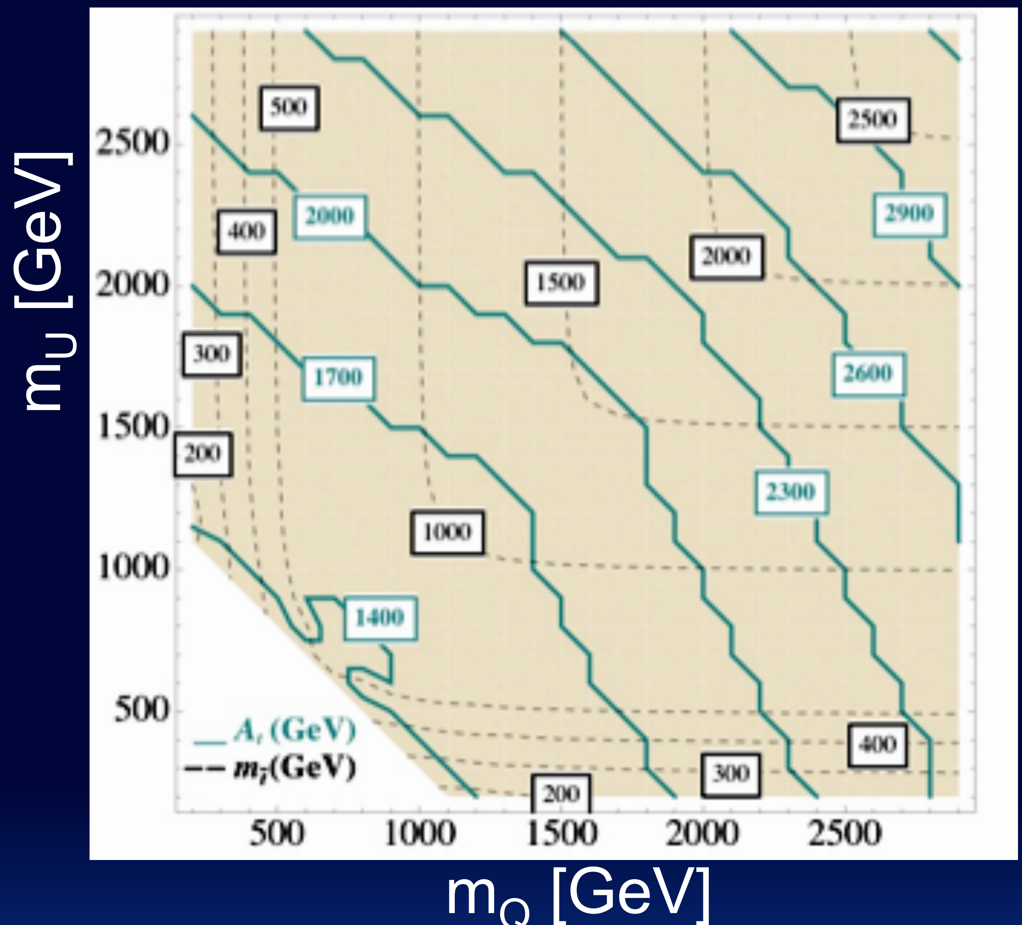
h may behave like the SM Higgs with m_h ~ 125 GeV

All other 3 Higgs bosons may be heavy (TeV range)

Or as light as a few hundred GeV (alignment)

The minimal SUSY Higgs mass and the Stop Sector

$m_h \sim 125.5$ GeV



Large Mixing in the stop sector

[Unless stops above 5 TeV]

Small stop effects on gluon fusion Higgs production

One stop can be light

[a few hundred GeV]

and the other heavy

[above a TeV]

or

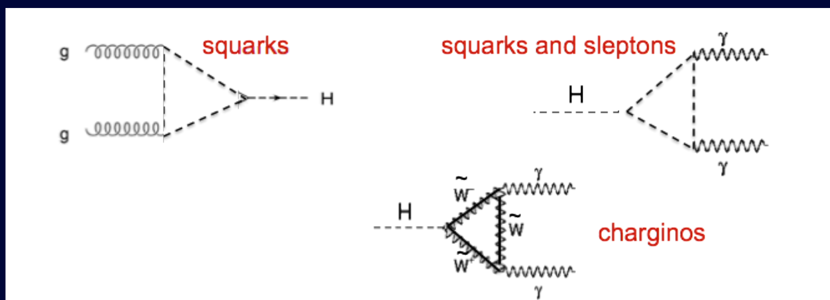
both stops can be light

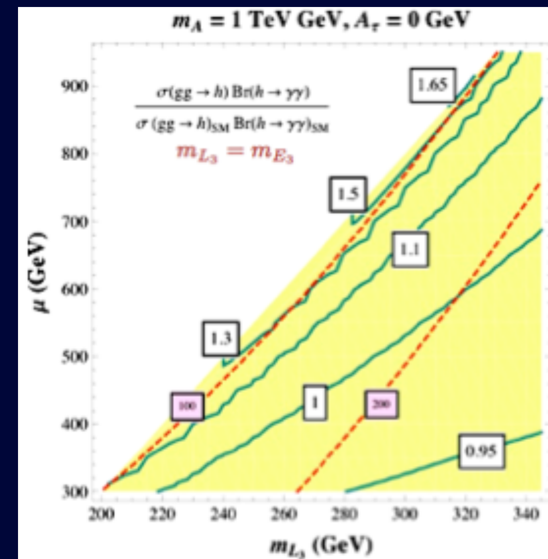
[about 500 GeV]

The new era of precision Higgs Physics

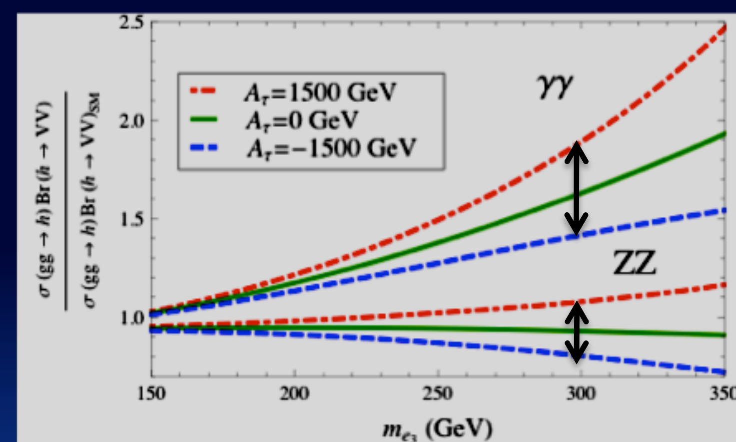
There could be one or more “large” ~10% deviations in Higgs couplings versus the SM, detectable at LHC or HL-LHC running

- New light charged or colored particles in loop-induced processes (at LHC reach) →





- Modification of tree level couplings due to Higgs mixing effects →



- Through vertex corrections to Higgs-fermion couplings: This destroys SM relation

$$BR(h \to bb)/BR(h \to \tau\tau) \sim m_b^2/m_\tau^2$$

- Decays to new or invisible particles

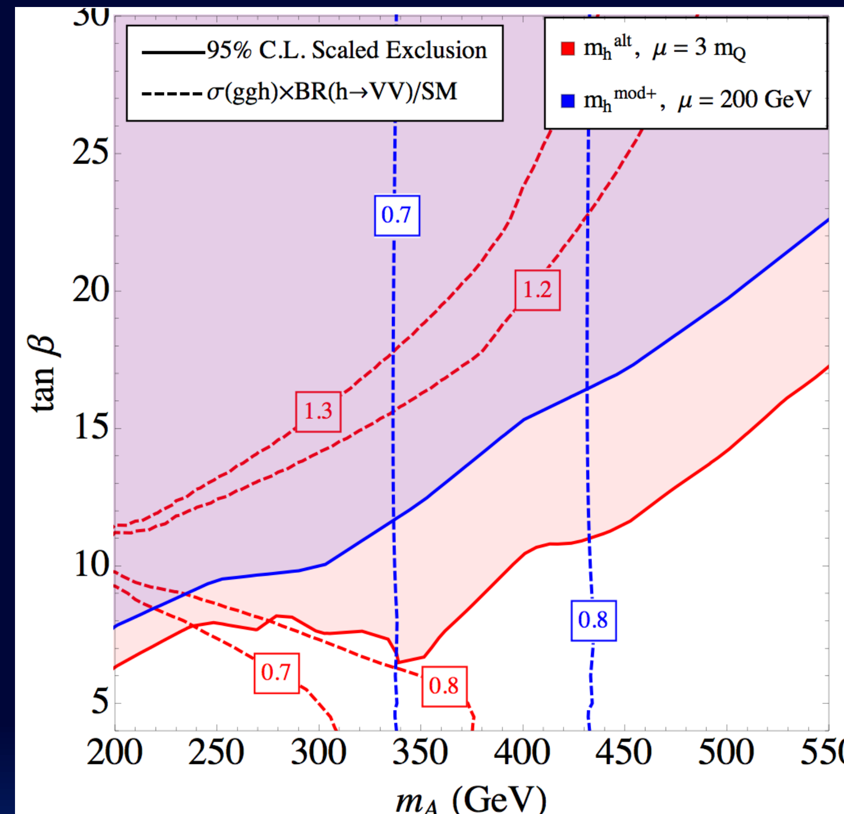
The new era of precision Higgs Physics

Additional Higgs Bosons Searches A/H → ττ and Precision Higgs

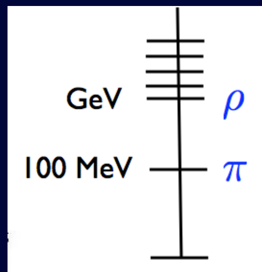
— σ(bbH/A+ggH/A) × BR(H/A → $\tau\,\tau$) (8 TeV)
--- σ(bbh+ggh) × BR(h → WW)/SM

Complementarity¨ crucial to probe SUSY Higgs sector

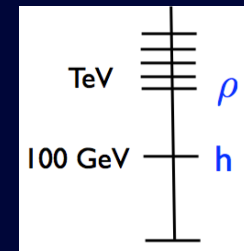
Correlations between deviations may reveal underlying physics



Composite Higgs Models
The Higgs as a pseudo Nambu-Goldstone Bosons (pNGB)



Inspired by pions in QCD



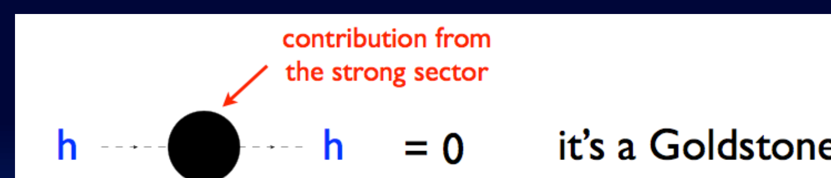
QCD with 2 flavors: global symmetry $SU(2)_L$ x $SU(2)_R$/ $SU(2)_V$.

π^{+-} π^0 are Goldstones associated to spontaneous breaking

$$g, g' \to 0 \quad \& \quad m_q \to 0$$
$$\Rightarrow m_\pi = 0$$
$$m_q \neq 0 \Rightarrow m_\pi^2 \simeq m_q B_0$$
$$e \neq 0 \Rightarrow \delta m_{\pi^\pm}^2 \simeq \frac{e^2}{16\pi^2} \Lambda_{QCD}^2$$

Higgs is light because is the pNGB
-- a kind of pion – of a new strong sector

Mass protected by the global symmetries



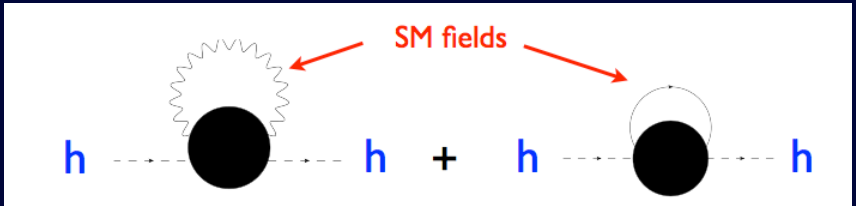
A tantalizing alternative to the strong dynamics realization of EWSB

Georgi,Kaplan'84

Higgs as a PNGB

Light Higgs since its mass arises from one loop

Mass generated at one loop: explicit breaking of global symmetry due to SM couplings



Dynamical EWSB: large set of vacua, some of them break $SU(2)_L \times U(1)_Y$

The Higgs potential depends on the chosen global symmetry
AND
on the fermion embedding in the representations of the symmetry group

Higgs mass challenging to compute due to strong dynamics behavior

$$\mathbf{m}_H^2 \propto m_t^2 M_T^2 / f^2$$

MANY NEW STATES being sought for at the LHC

Minimal Composite Higgs models phenomenology

-- All About Symmetries --

Choosing the global symmetry [SO(5)] broken to a smaller symmetry group [SO(4)]
-- at an intermediate scale f larger the electroweak scale -- such that:
the Higgs can be a pNBG, the SM gauge group remains unbroken until the EW scale
and there is a custodial symmetry that protects the model from radiative corrections

Higgs couplings to W/Z determined by the gauge groups involved

SO(5) → SO(4)

Higgs couplings to SM fermions depend on fermion embedding

With Notation $MCHM_{Q\text{-}U\text{-}D}$

5, 10,
5-5-10, 5-10-10, 10-5-10
14-14-10, 14-1-10

Representations of SO(5)

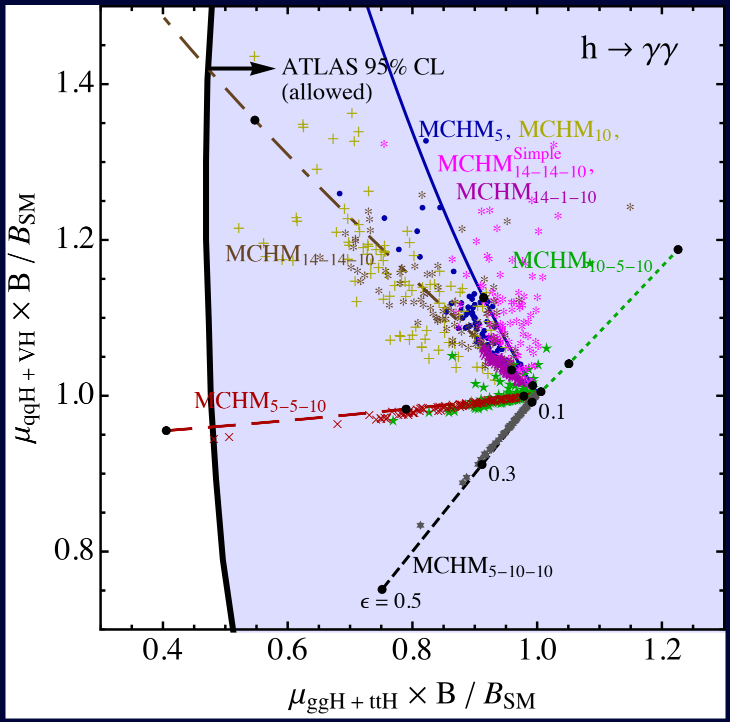
Generic features:

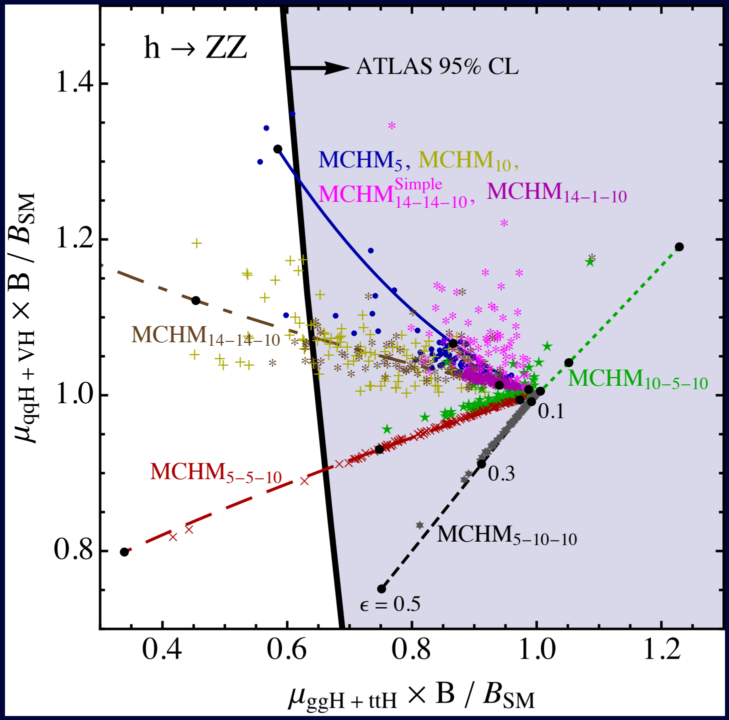
Suppression of all partial decay widths
Suppression of all production modes
Enhancement/Suppression of BR's dep. on the effect of the total width suppression

→ Driven by the idea that heavy SM fermions are a mixture of elementary and composite states

Minimal Composite Higgs models confronting data

h to di-photons **h to ZZ**





- light fermions (TeV range and possibly exotic charges) may be at LHC reach
- More data on Higgs observables will distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics

Deep Connections

The Higgs

and the Mysteries of Matter

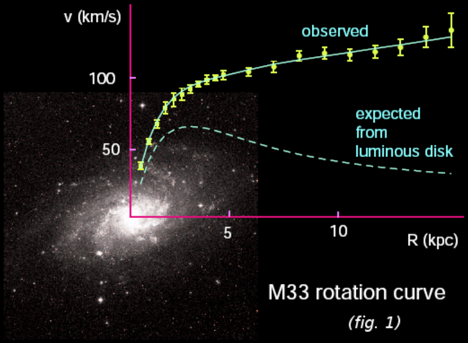
The power of the dark side

Holds the Universe together and makes ***85% of all the matter in it!***

Interacts very weakly
(not charged)

Gravity

Higgs-like Interactions



M33 rotation curve
(fig. 1)

WIMP Dark Matter ?

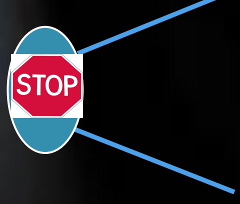
- DM = yet unknown, heavy, neutral elementary particle/s
- Mass estimate (model dependent) from observed dark matter abundance:

$$M_{DM} \sim 100 - 1000 \text{ GeV}$$

and fits well with a weakly interacting particle = WIMP

CAVEAT: To avoid decay of a WIMP to lighter visible matter, theorists invented a symmetry: "dark matter charge" such that

DM - - - - - -



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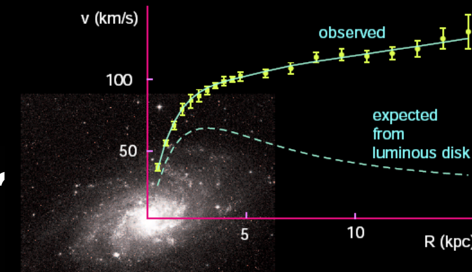


M33 rotation curve
(fig. 1)

SUSY and the WIMP Miracle ?

- If the LSP is the lightest neutralino it will behave as WIMP dark matter
- In the MSSM the lightest neutralino is generically a mixture of the Bino, Wino, and the two Higgsinos
- If you are more ambitious, you can try to require that the LSP is a thermal relic with the correct abundance to explain all ALL dark matter

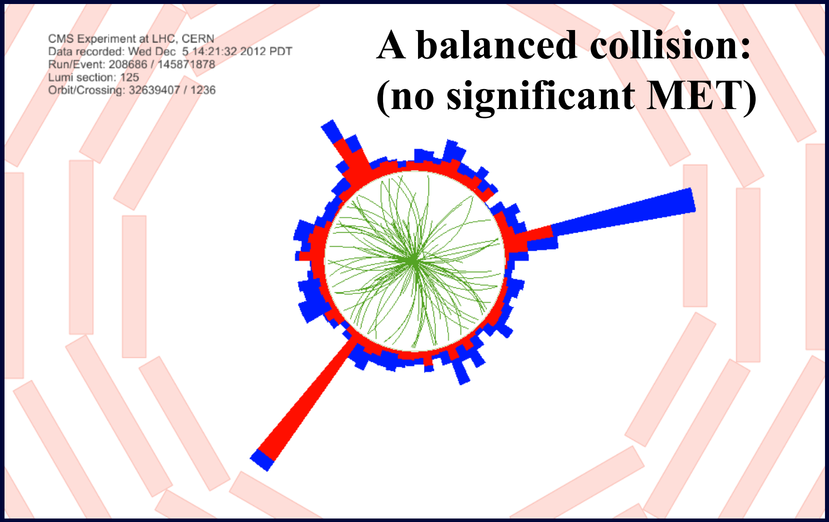
We are testing the outrageous idea

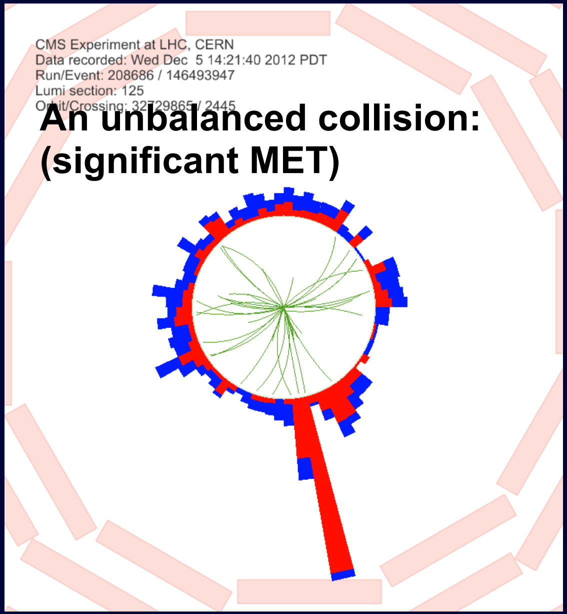
of Dark Matter using

accelerators, telescopes and specialized detectors!

A priority for Particle Physics and Cosmology

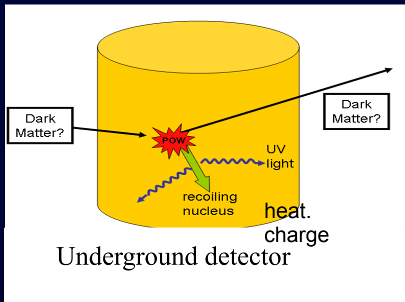
We can create Dark Matter at the LHC





Counting the energy we put in and the energy that comes out
if a lot is missing we created Dark Matter

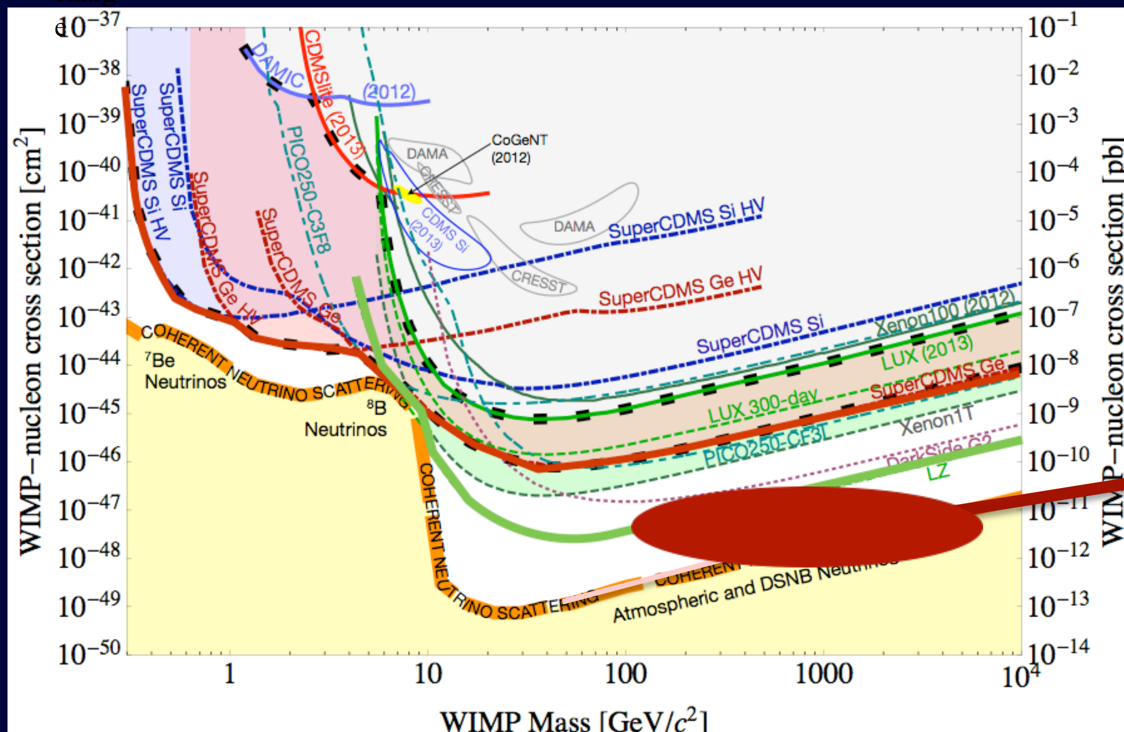
We can also produce dark matter in the decay of other new particles
charged under the dark sector,
e.g. in the decays of stops, sbottoms and gluinos

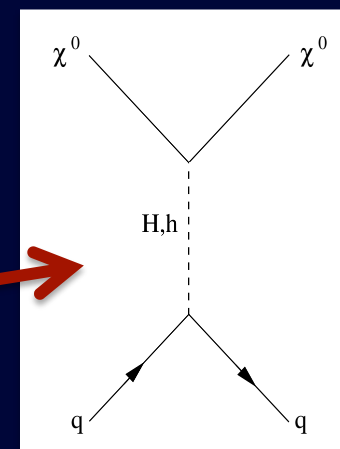


Dark Matter Direct Detection:

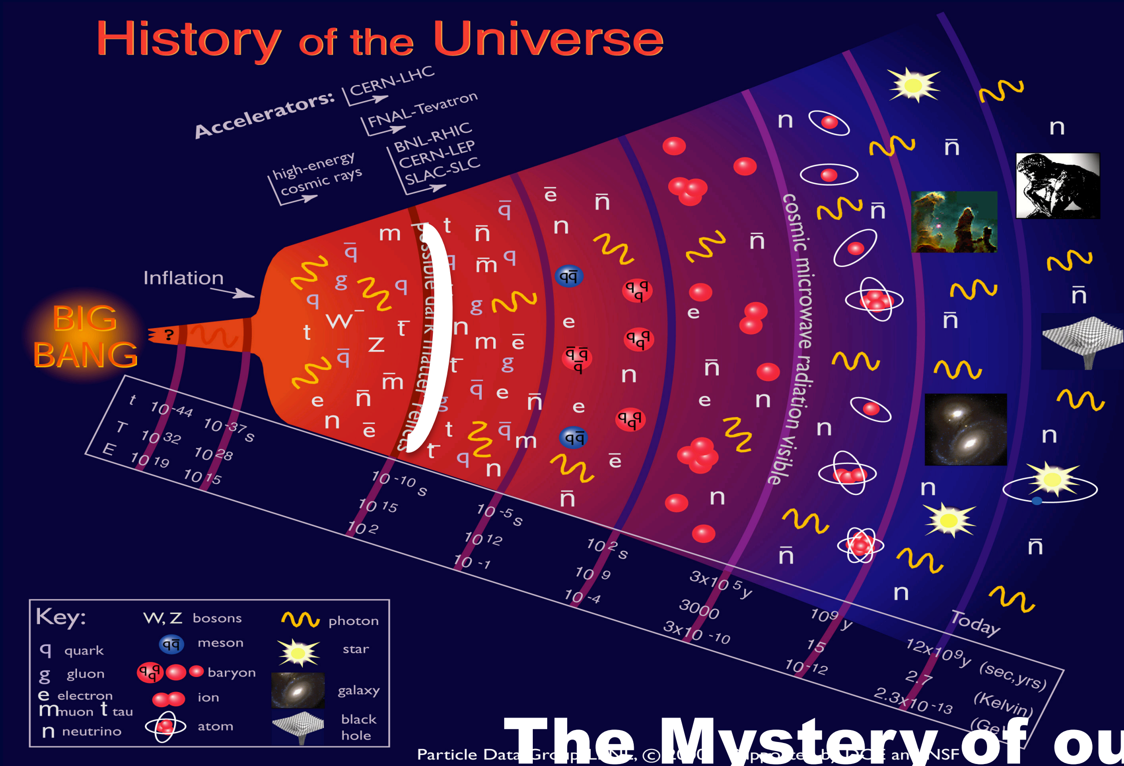
It can *collide with a single nucleus in the detector and be observed*

Starting to Probe the Higgs Portal





- Mixed Wino-Higssino or Bino-Higgsino ➔ can have suppressed couplings (with the Higgs bosons by tuning M_2 (M_1), tan β and μ
- Relevant destructive interference between h and H possible



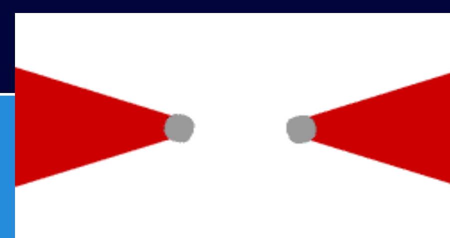
At the BIG BANG :

Equal amounts of Matter and Anti-matter

The Mystery of our Existence

There was a big matter-antimatter battle…

A tiny amount of matter survived …



Matter

10,000,000,001

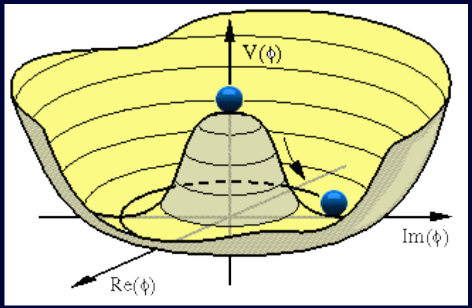
Antimatter

10,000,000,000

Electroweak Baryogenesis

What generated the small imbalance between matter and antimatter? How did it happen? When?

- **Out of Equilibrium processes**
- **Violation of CP Symmetry that relates matter with antimatter**
- **Baryon number violation**



All the above happens at the EW phase transition in the SM but the Higgs is too heavy and the CP violation is too small

Tests of Baryogenesis

- Baryogenesis at the Electroweak Scale can explain our existence and can be tested at the LHC
- New particles that couple strongly to the Higgs can make this work
- But, requires going beyond Minimal SUSY with additional CP violation sources
- The new particles should be at LHC reach
- CP violation may be observed at LHC and or other experiments   e.g. Electric Dipole Moment

Revolutionary advances
in our understanding of the Universe
are driven by
powerful ideas and powerful instruments

Higgs Mechanism ⟷ LHC

What's Next?

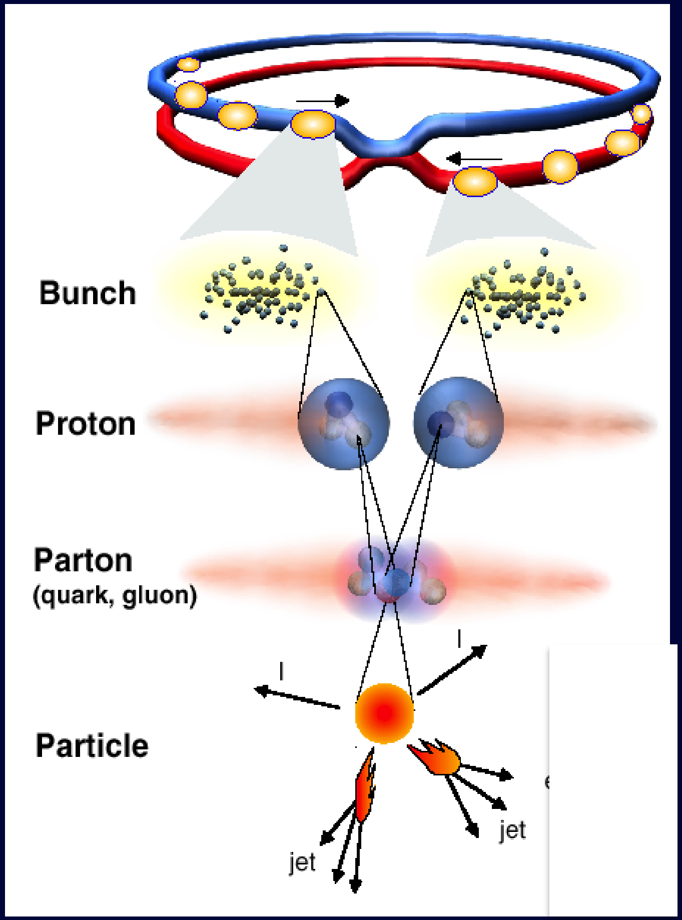
The existence of Dark Matter and the Matter-Antimatter Imbalance implies new physics which may be accessible to experiment in this decade

The Higgs boson may play a key role in understanding both mysteries of matter

EXTRAS

LHC:
why so huge and why circular ?

- Charged particles accelerated by electric fields
- Protons are sent in a circular path and they get several "kicks" with electric fields every time they come around
- A linear accelerator would be prohibitively long
- Protons are bent in a circular path with magnets
- The higher the energy the harder it is to bend the protons



The size of the ring is set by the strongest magnets we can build

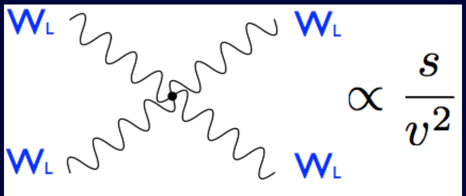
About a Billion proton-proton collisions per second

About 100 particles produced per collision

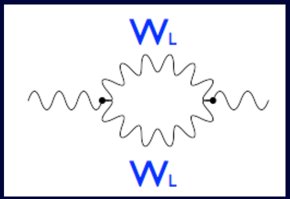
Is The Higgs all we need ?

The Higgs is special:

Without the Higgs, the calculability power of the SM is spoiled



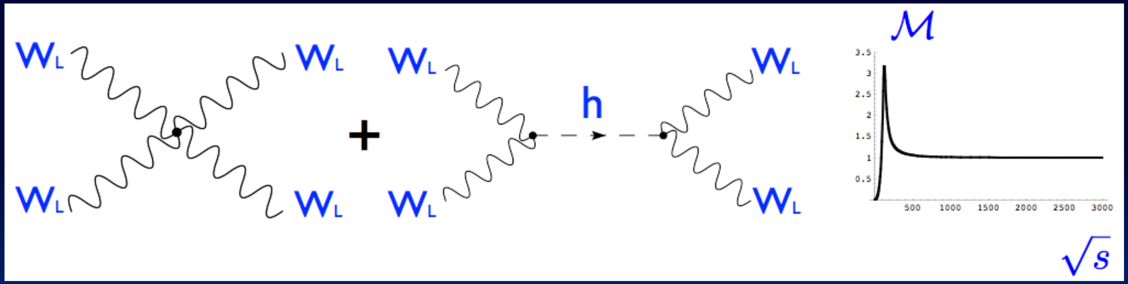
Unitarity lost at high energies



Loops are not finite

New Physics is needed at the EW scale

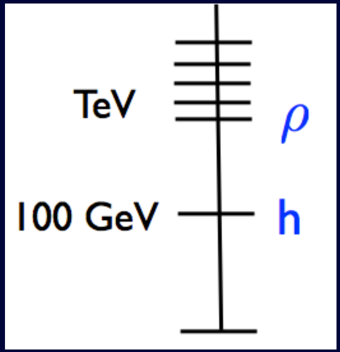
With the SM Higgs calculability is recovered (m_H<170 GeV)



Loops are finite

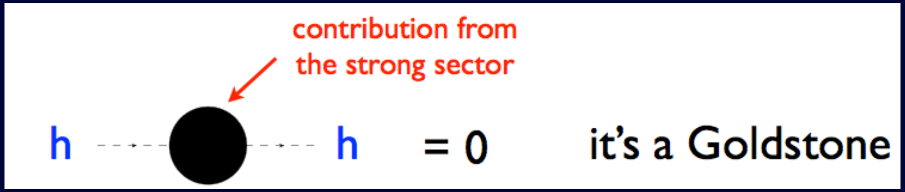
New Physics only needed to explain gravity

Composite Higgs



Higgs is light because is the Pseudo Goldstone Boson of a global symmetry
-- like pions of a new strong sector (QCD inspired) --

Higgs mass protected by global symmetry



Generated at one loop: breaking of global symmetry due to SM couplings

Higgs mass difficult to compute due to strong dynamics behavior

$$m_H^2 \approx m_t^2 M_T^2 / f^2$$

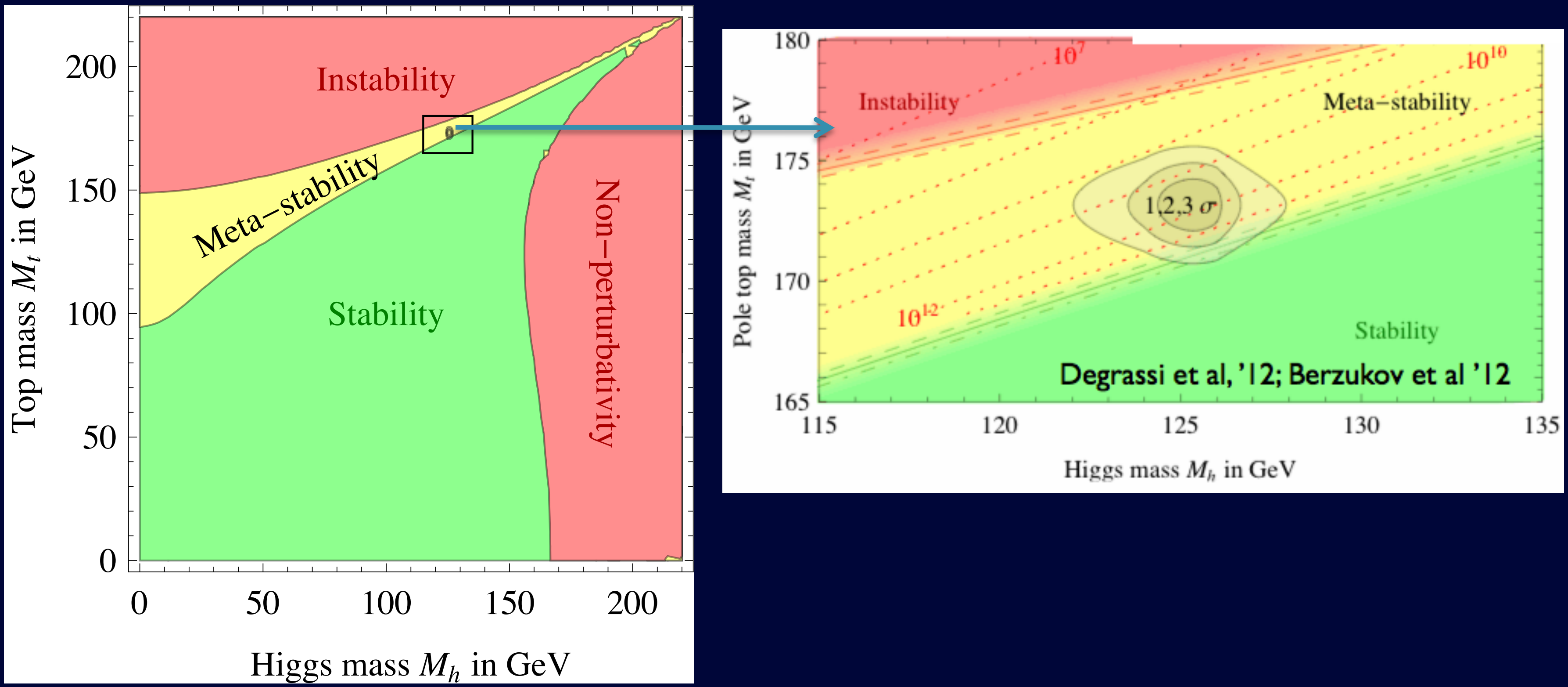
Higgs couplings to W/Z determine by the gauge groups involved

i.e. MCHM_X ➔ SO(5)/SO(4)

Higgs couplings to SM fermions depend on fermion embedding X

MANY NEW STATES being sought for at the LHC

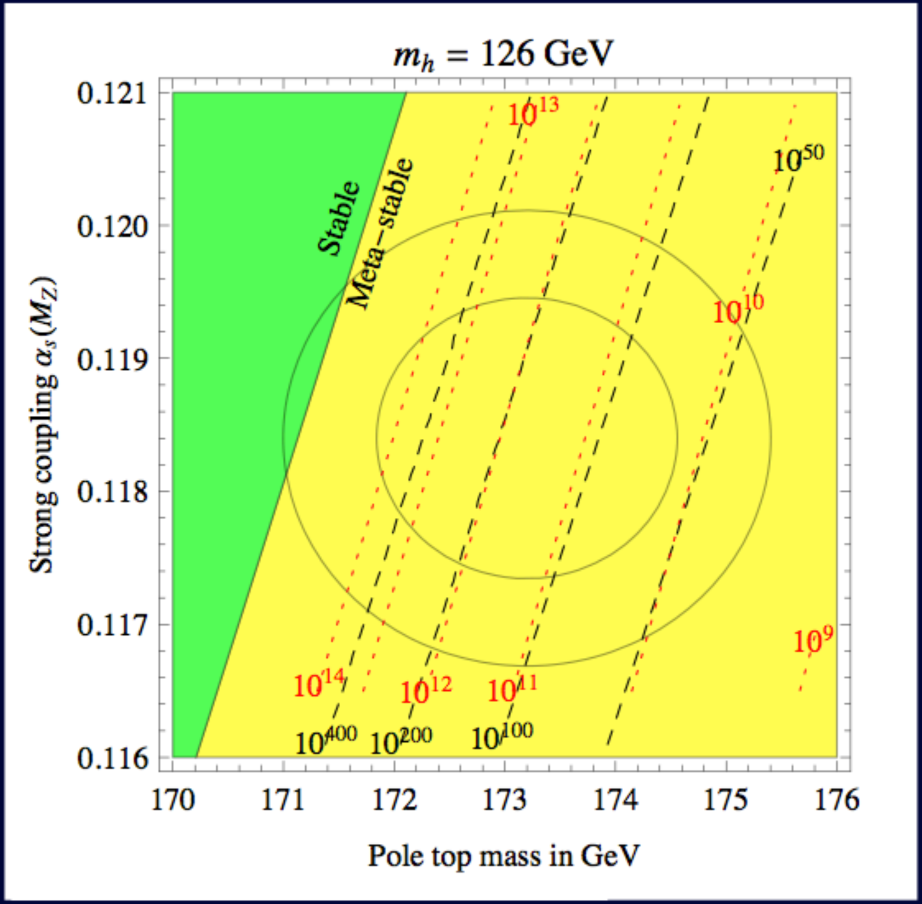
The Higgs and the fate of our universe



It might be 10^{100} years before the fatal bubble forms or, we may be very unlucky…

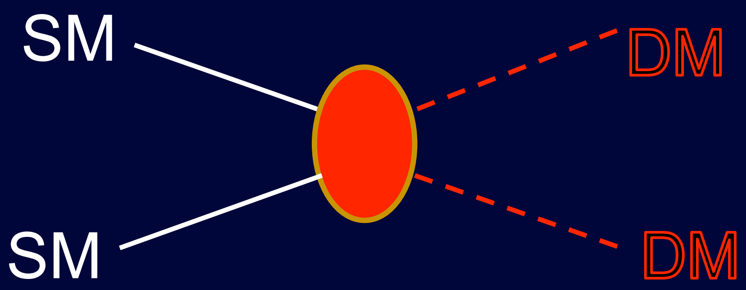
Or a new symmetry of nature may stabilize the universe

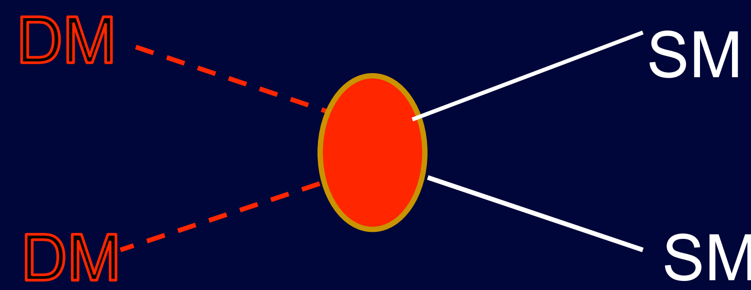
El bosón de Higgs y el destino del Universo



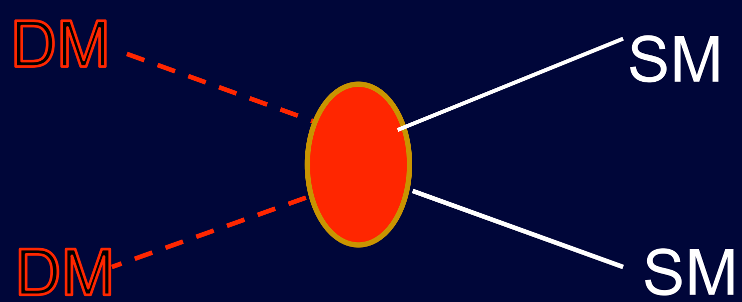
The History of the Dark Matter Abundance

- Dark matter produced in the hot early Universe can pair-wise annihilate (thermal equilibrium)





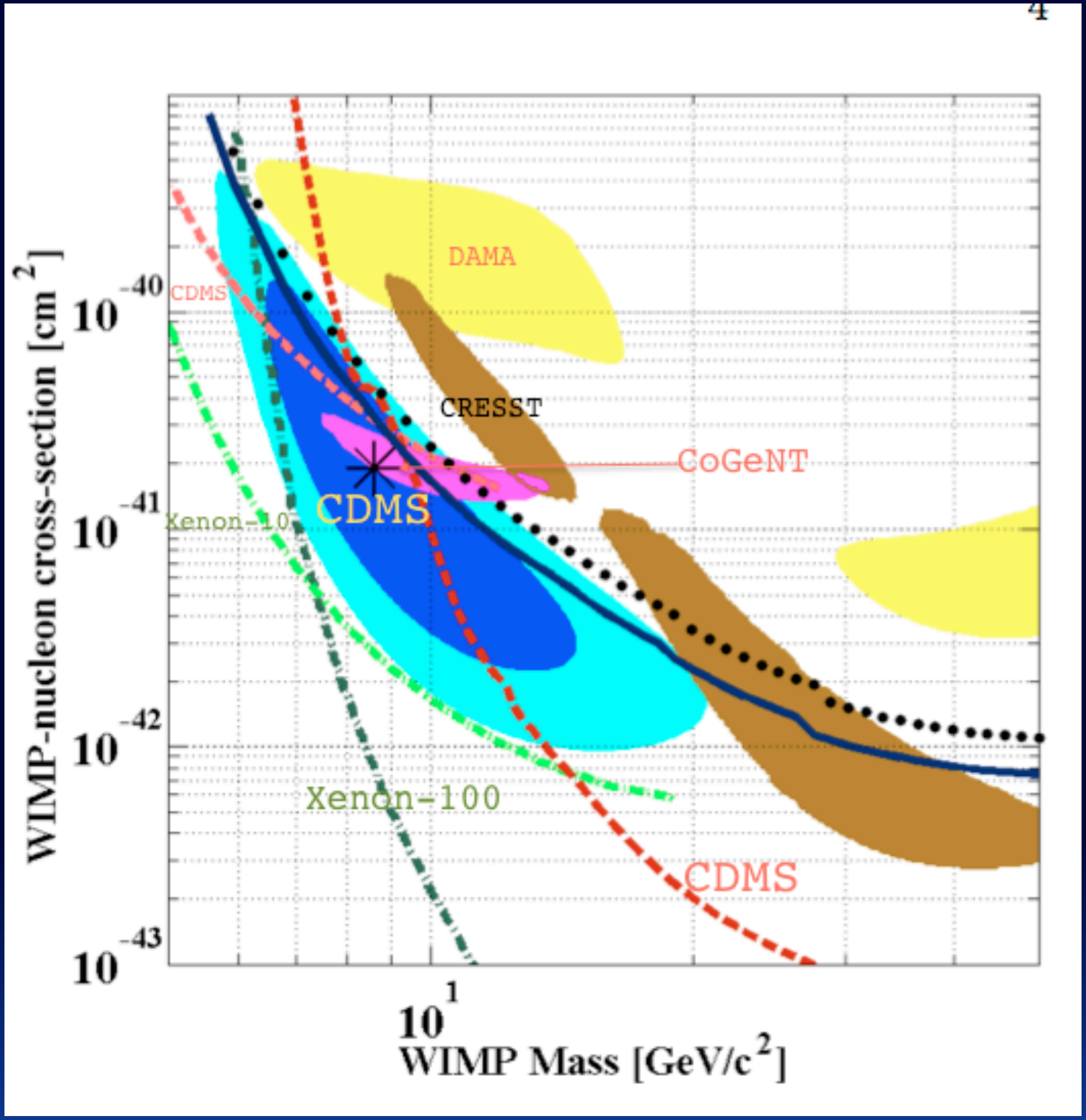
- Dark Matter density decreases as the Universe expands



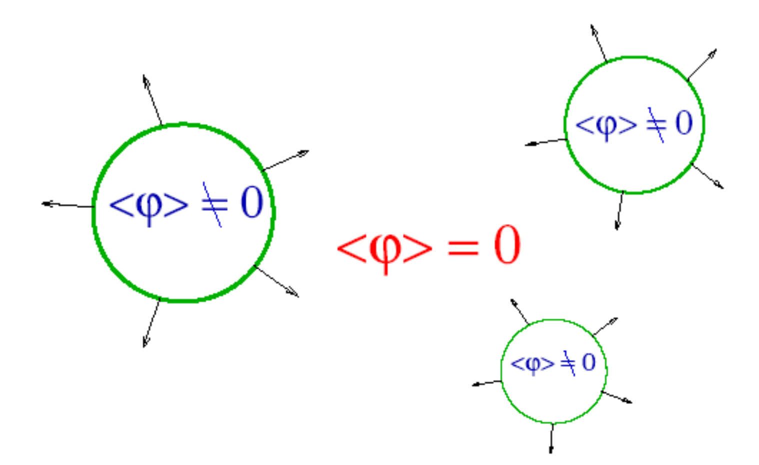
- ***Finally DM annihilation stops***

The *smaller* the rate for pair annihilation,
the *larger* is the Dark Matter abundance (relic) observed today

There are some signals in the "excluded" region that could be Dark Matter

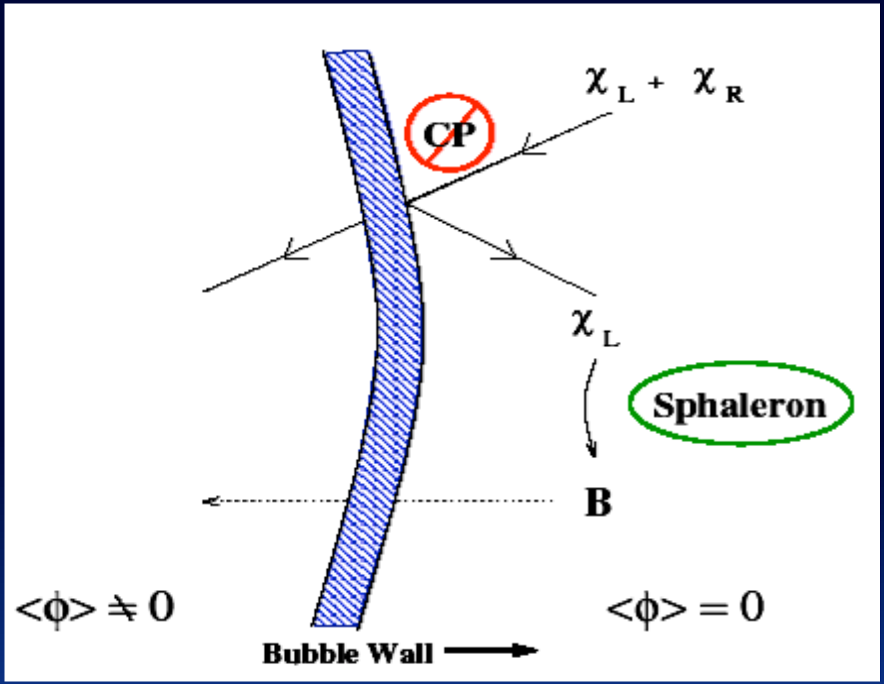


At the temperature at which the Higgs becomes active

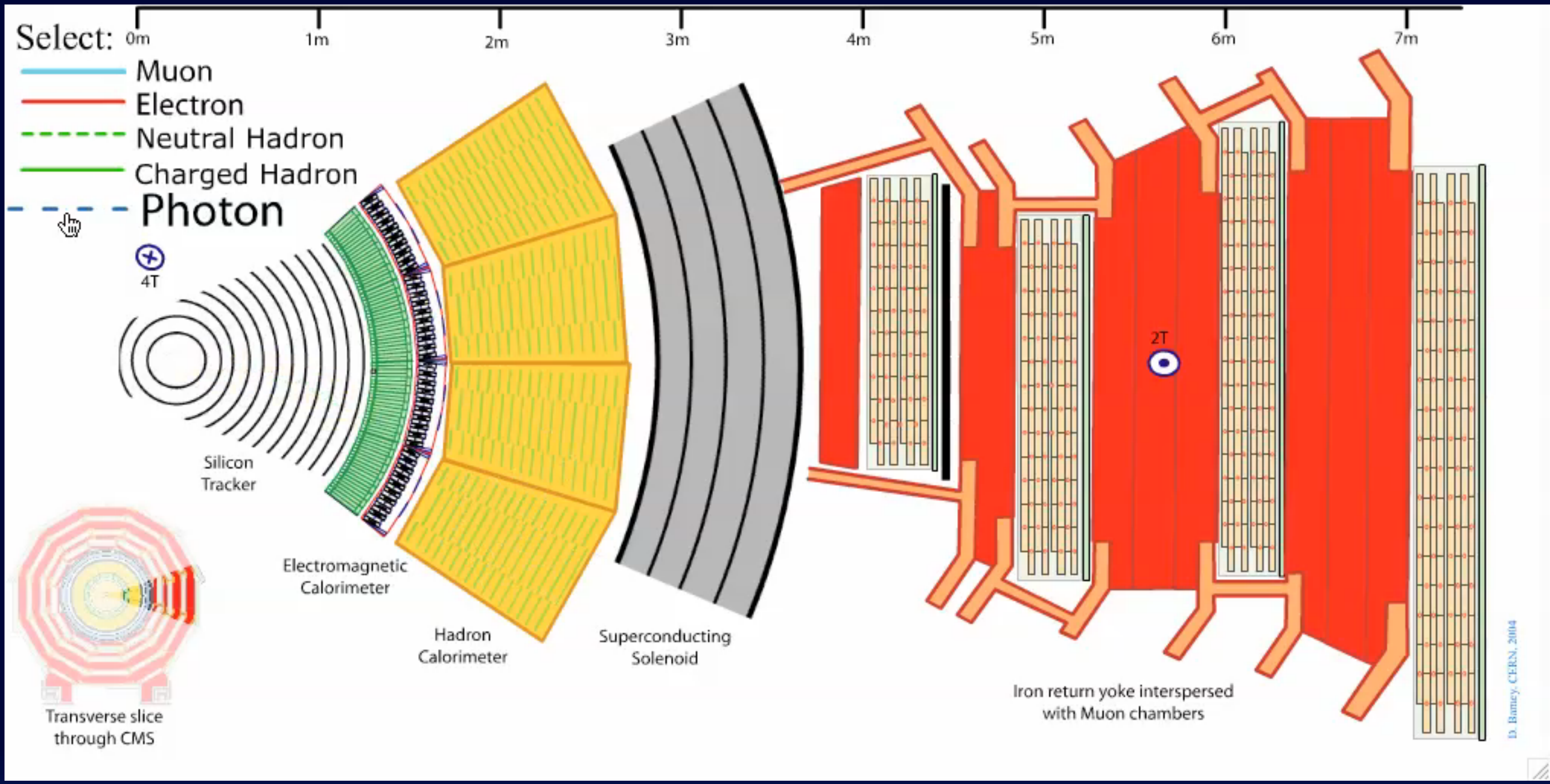


- Bubbles of true vacua start to form and expand
- CP violating currents are generated at the bubble walls
- Quantum configurations generate a net matter-antimatter asymmetry

The Higgs potential must allow for a specific type of transition to the SSB vacuum, such that the created matter-antimatter asymmetry stays frozen until today

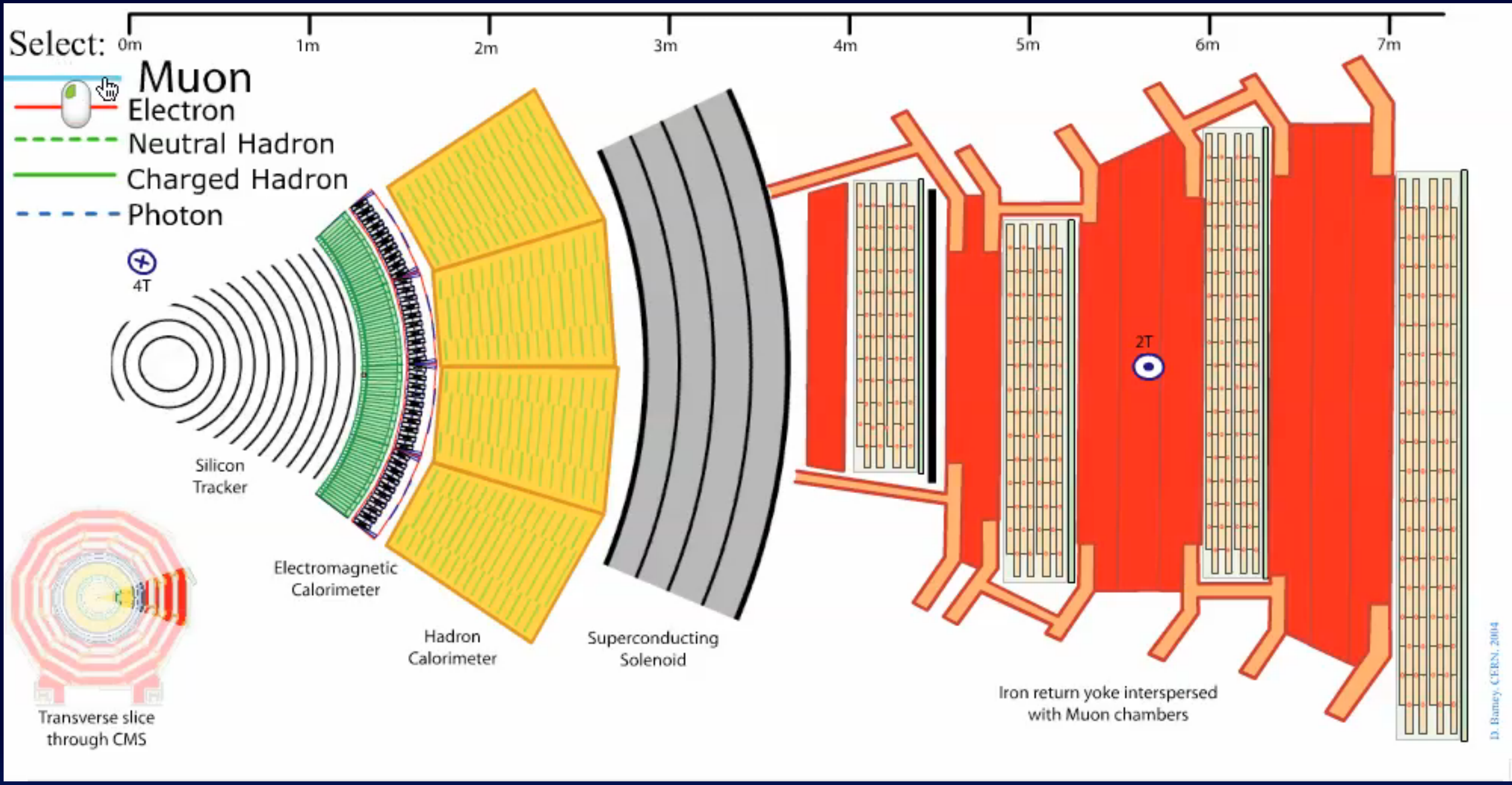


What the detectors detect



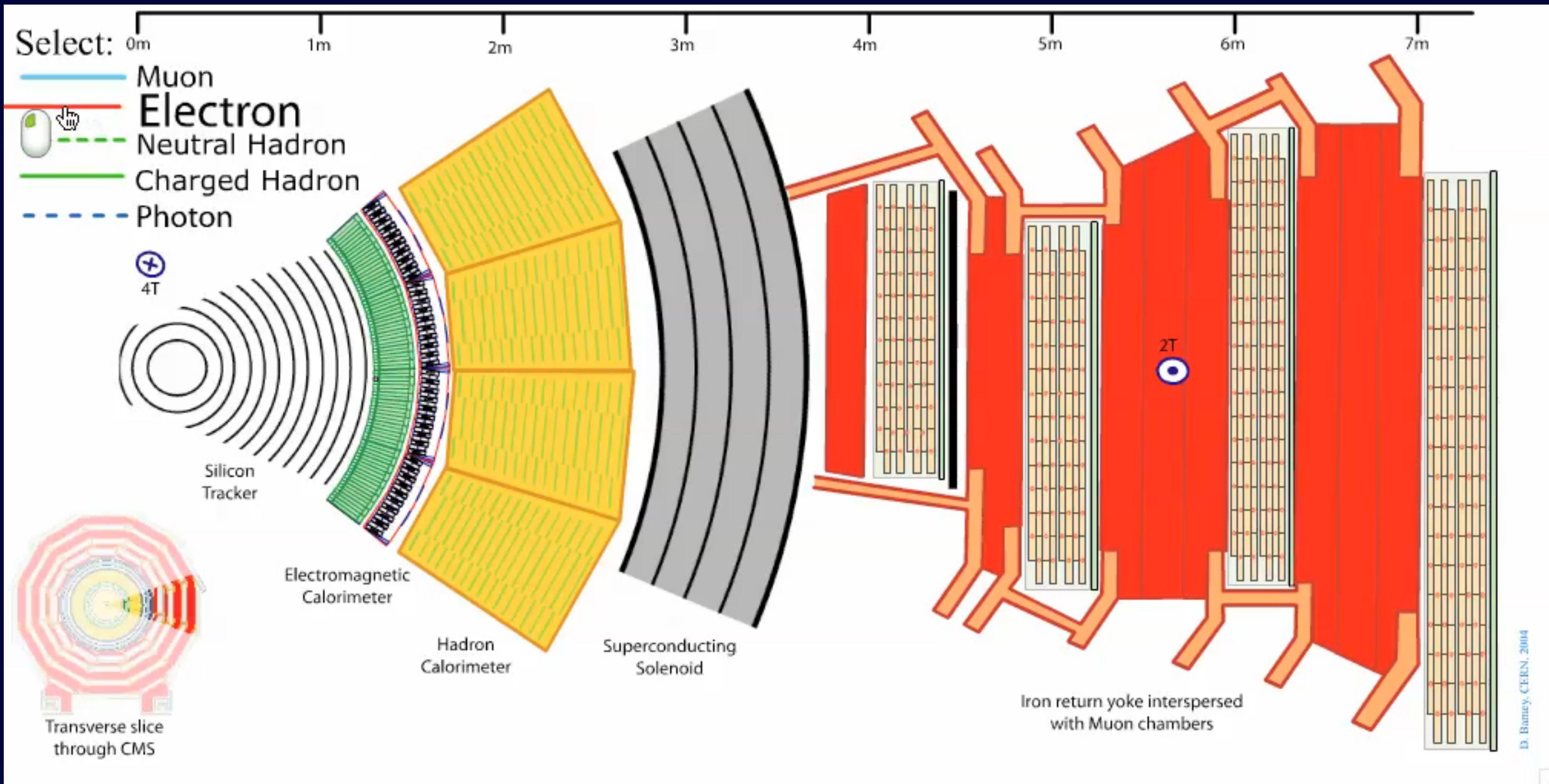
We look for the tracks that a particle leaves behind

What the detectors detect



We see signals when the layers of the detector stop the particles as they fly out

What the detectors detect



We see signals when the layers of the detector stop the particles as they fly out

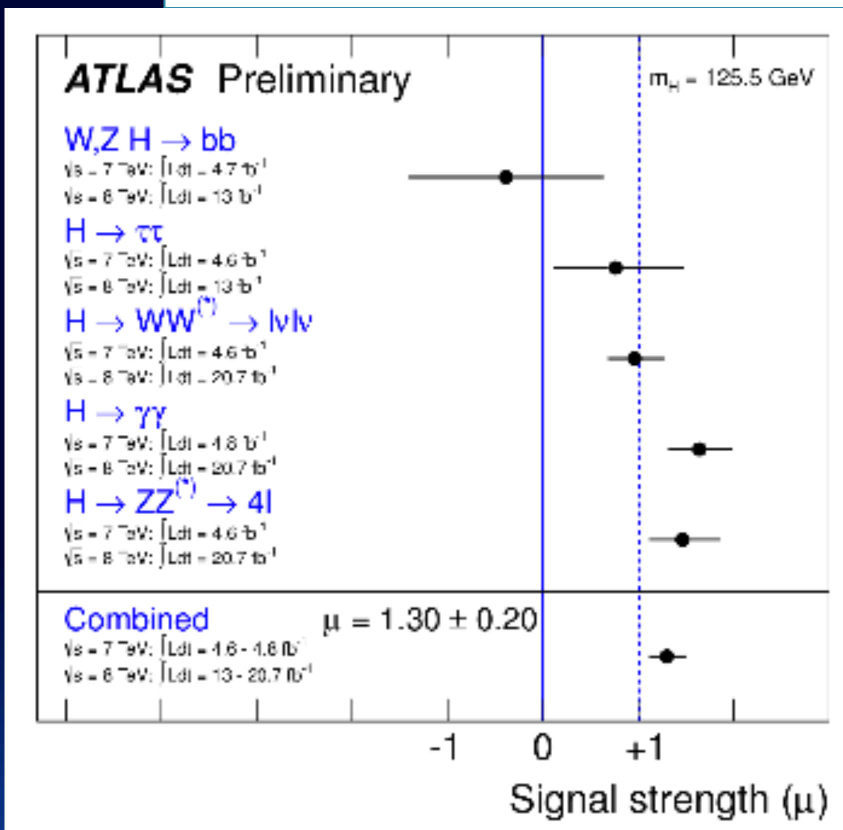
2012-2013: an amazing year for Physics

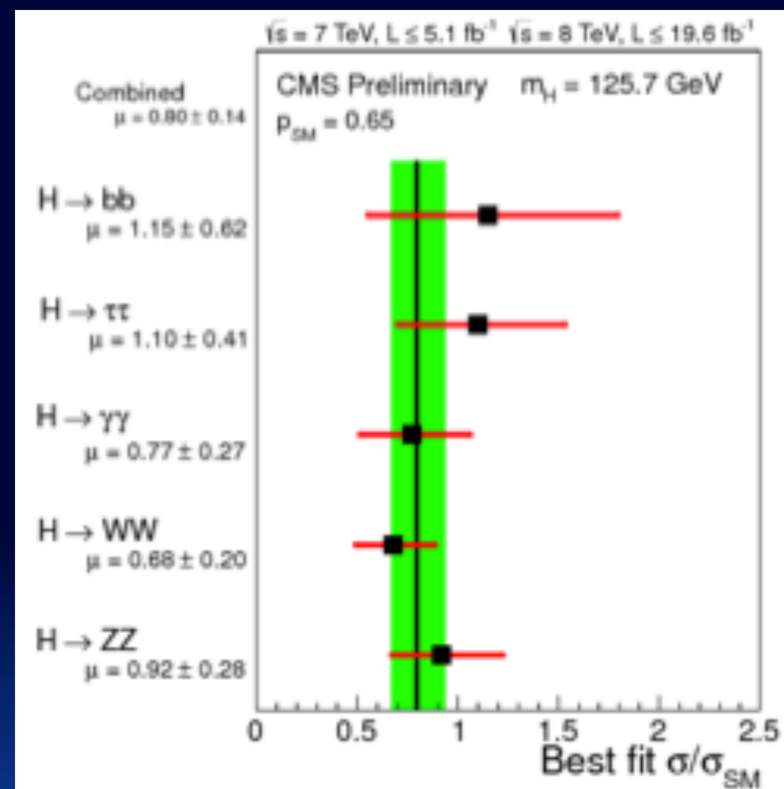
No doubts that a new type of particle has been discovered

CMS: $m_h \sim 125.8$ GeV (in ZZ); $m_h = 124.9.$ GeV (in $\gamma\gamma$)

ATLAS: $m_h = 124.3$ GeV (in ZZ); $m_h = 126.8$ GeV (in $\gamma\gamma$)

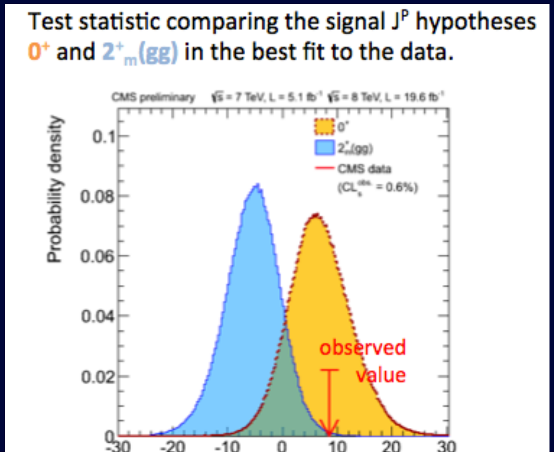
more than a 5σ signal in each channel

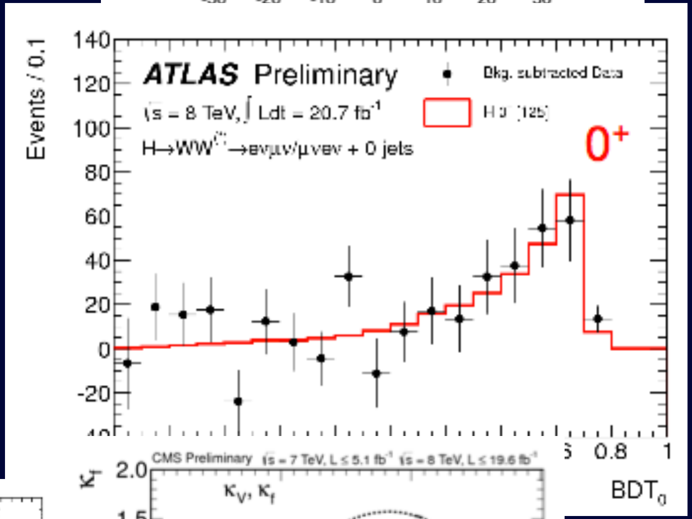


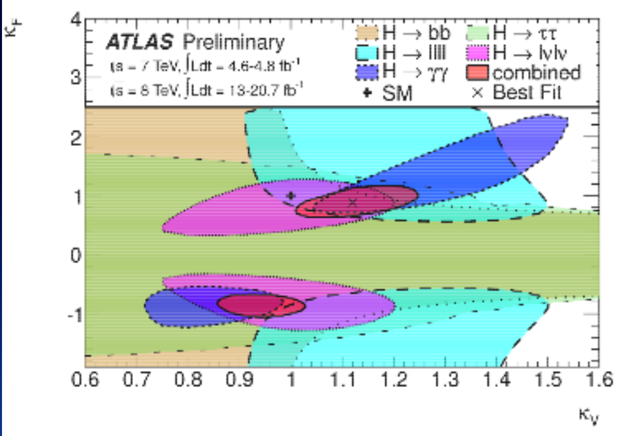


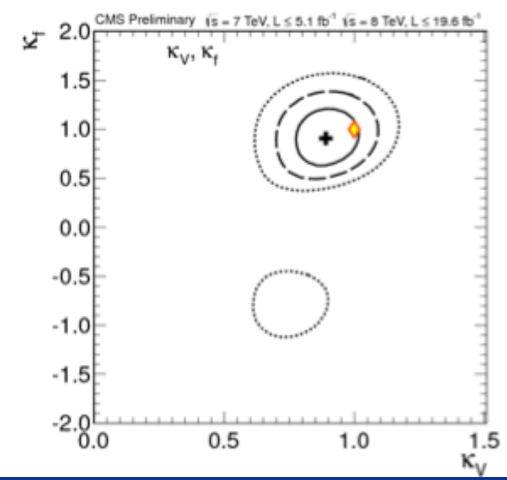
The SM Scalar Boson:

- Spin 0
- Neutral CP even component of a complex $SU(2)_L$ doublet
- Couples to weak gauge bosons as $g_{WWH}/g_{ZZH} = m_W^2/m_Z^2$
- Couplings to SM fermions proportional to fermion masses
- Self-coupling strength determined its mass (and v = 246 GeV)







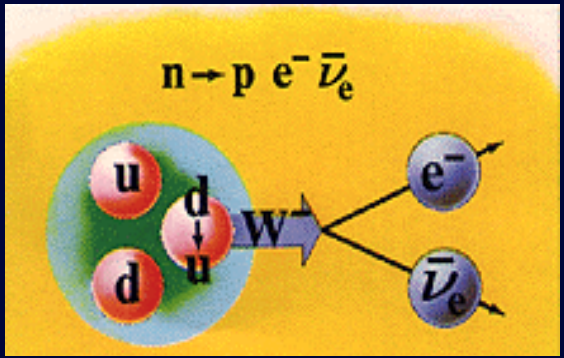


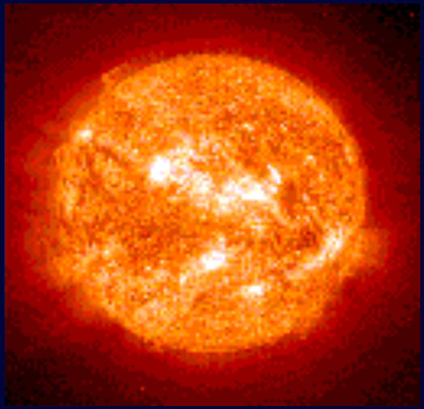
The weak interactions

• Are short range

demand massive force carriers (W & Z)

$$F_W \approx e^{-M_W d}/d$$





$$m_W = 80.449 \pm 0.034\,GeV$$

Explains solar fusion

• Have a chiral structure

left handed fermions have different weak charges than right handed ones

Very different from infinite range QED, with massless photon

U.S. plays a leading role in LHC discovery

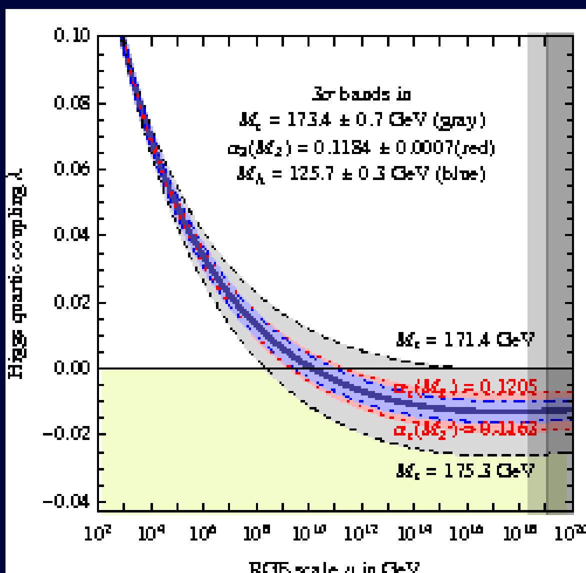
- U.S. = 1/3 of CMS, the largest contingent
- U.S. = 1/5 of ATLAS
- CMS/ATLAS leadership: spokesperson, upgrade coordinator, deputy spokespersons, physics coordinators, managers, critical hands-on roles in discovery analyses, hardware, computing
- 1,700 scientists, students, engineers and technicians
- 93 universities,
  7 national labs, 32 states

The Higgs and the fate of our universe

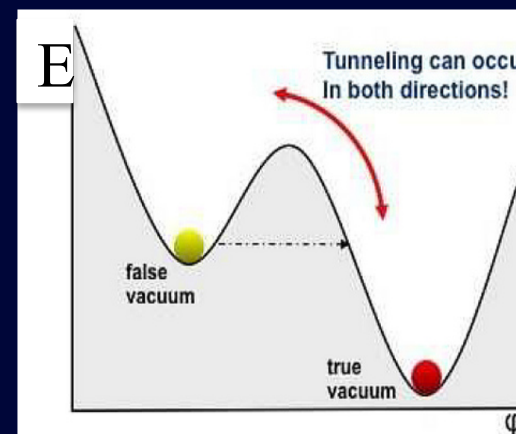
In the SM: $V(\Phi) = -m^2|\Phi|^2 + \lambda\,(\Phi^+\Phi)^2$ and $m^2_H = 2\,\lambda v^2$

➔ $\lambda \sim 0.13$ and $|m|^2 \sim 88$ GeV (v = 246 GeV)

λ evolves with energy



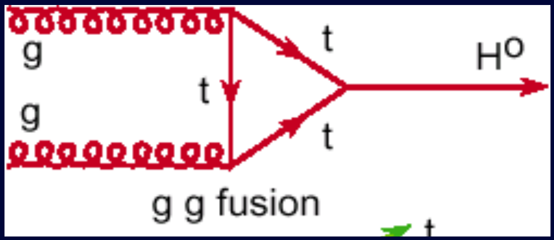
The EW vacuum is metastable

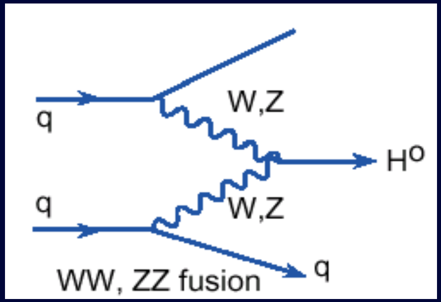


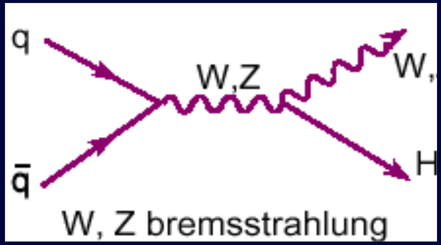
Slow evolution of λ at high energies saves the EW vacuum from early collapse

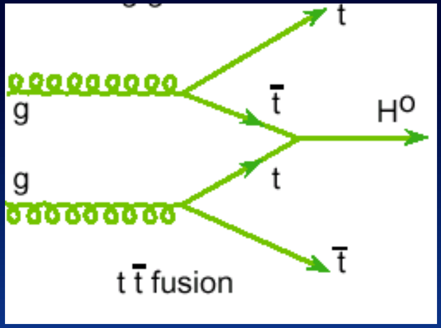
The peculiar behavior of λ:
A coincidence, some special dynamics/new symmetry at high energies?
Or not there at all ? ➔ new physics at low energy scale

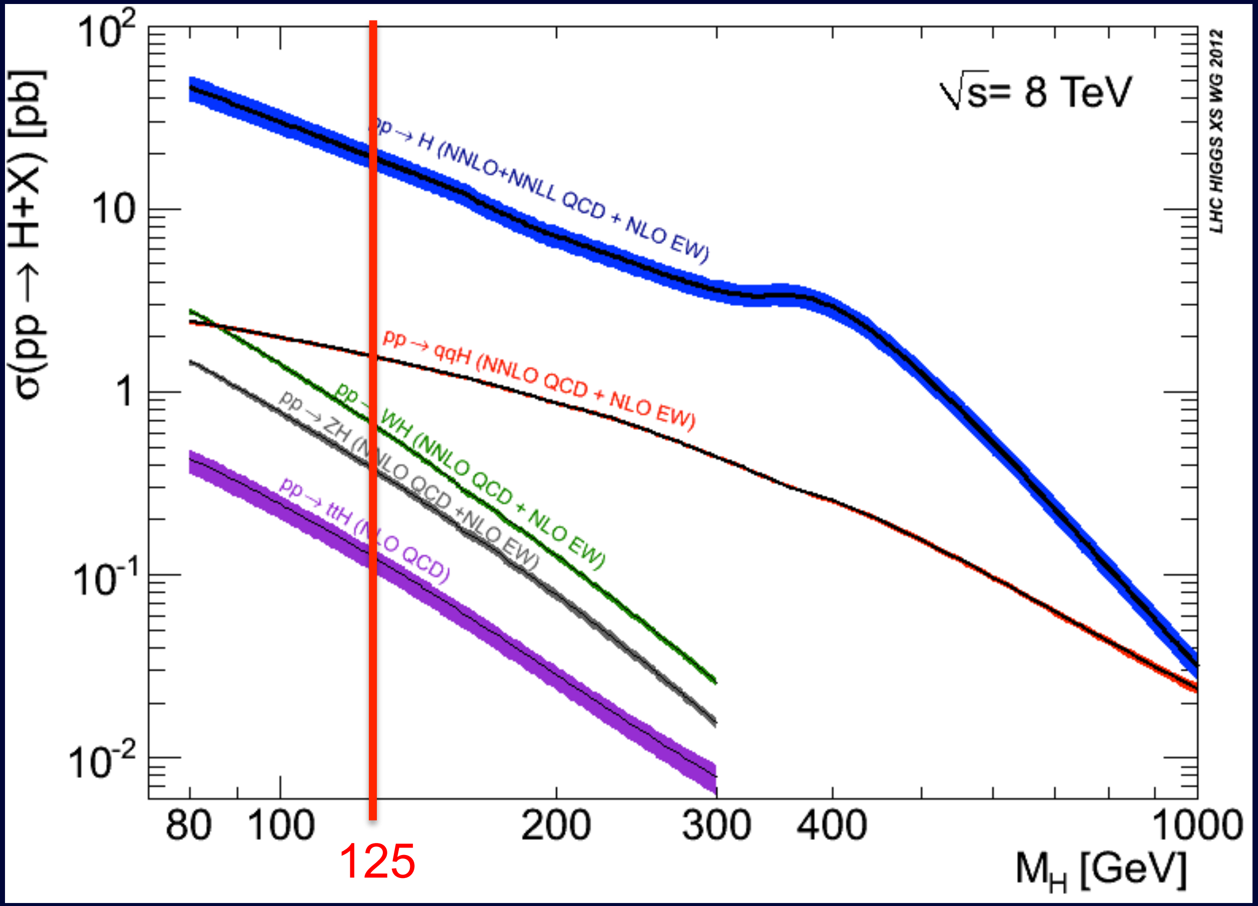
The SM Higgs at the LHC







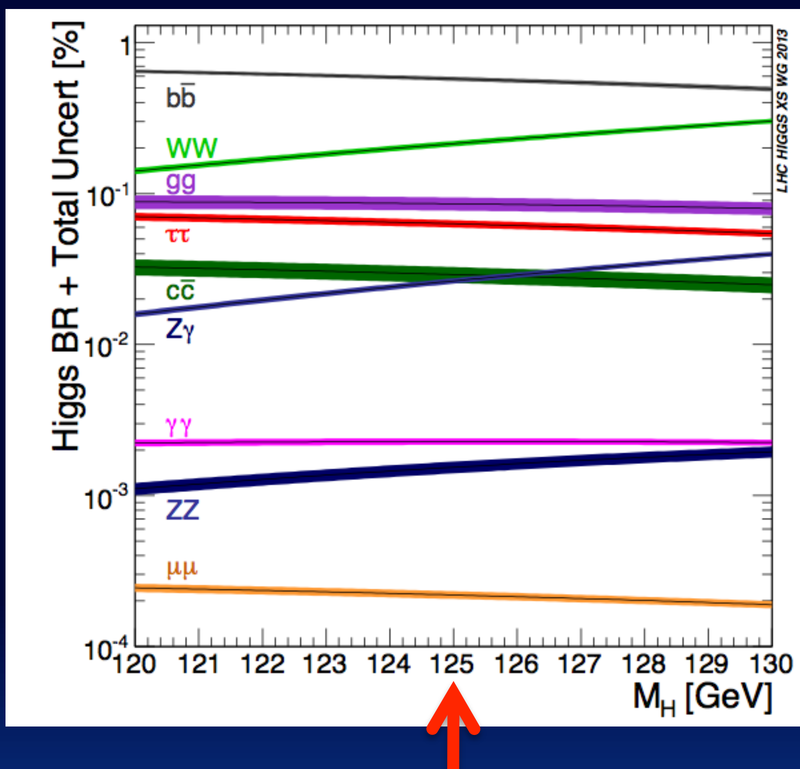


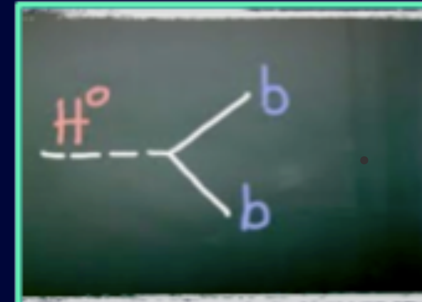


Much recent progress from theorists in computing these production processes with high accuracy

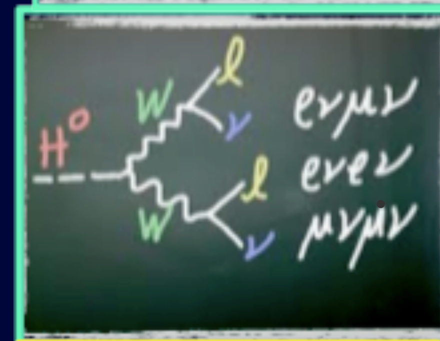
Higgs decays:

Higgs decays after about 100 yocktoseconds into various pairs of lighter particles

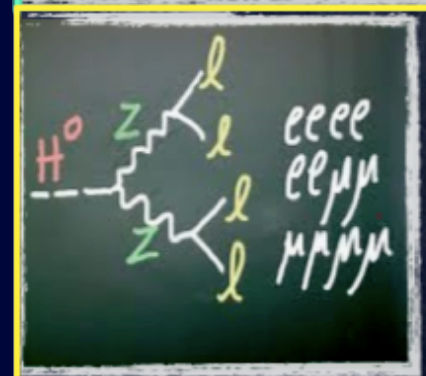




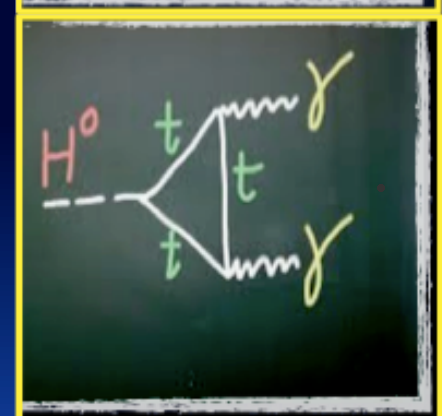
Lots of background



Neutrinos not detected



Rare but “Golden” channel



Rare but relatively clean

Two possible Solutions:

Supersymmetry: a fermion-boson symmetry

The Higgs remains elementary but its mass is protected by the new fermion-boson symmetry

$$\delta \mathbf{m^2} = \sum_{\mathbf{F}} \mathbf{g_F} \lambda_{\mathbf{F}}^{\mathbf{2}} \frac{(\mathbf{m_B^2} - \mathbf{m_F^2})}{\mathbf{32}\pi^{\mathbf{2}}} \log(\mathbf{Q^2}/\mu^{\mathbf{2}}) \qquad \delta \mathbf{m^2} \propto \mathbf{M_{SUSY}^2}$$

SUSY and Naturalness : **Higgsinos, stops,** and gluinos should not be too much heavier than the electroweak scale

Composite Higgs Models:

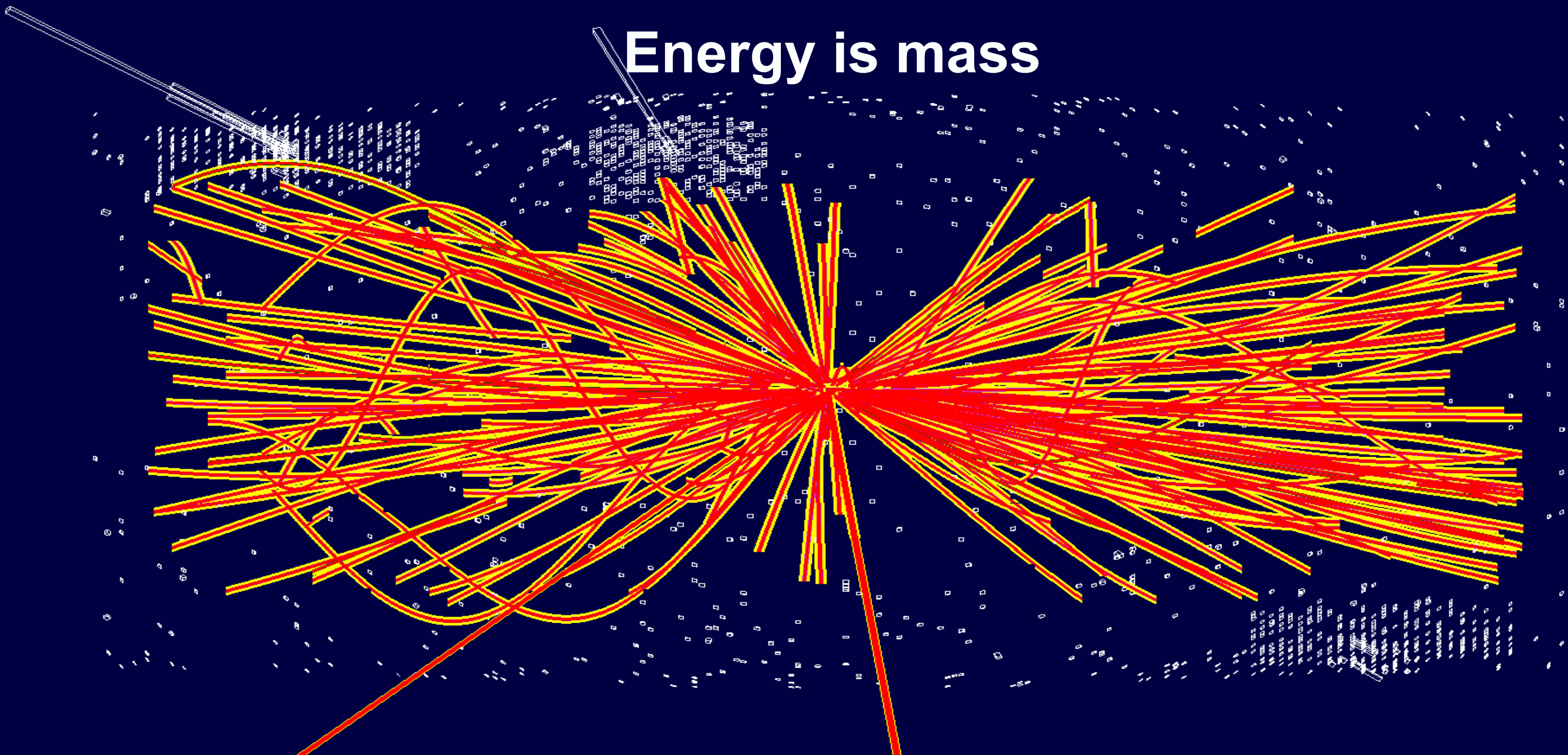
The Higgs does not exist above a certain scale, at which new strong dynamics takes place

Both options imply changes in the Higgs phenomenology and New particles that may be seen at the LHC

How do we search for the Higgs?

Smashing Particles at High Energy Accelerators to create it

Energy is mass



And searching for known particles into which the Higgs decays almost instantly

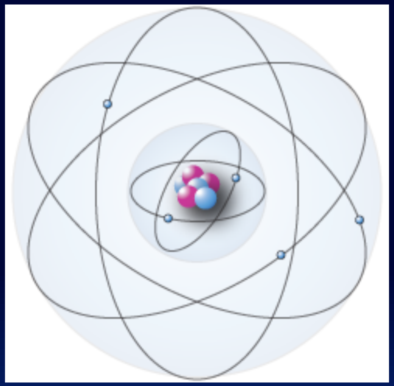
At huge Particle Accelerators,

Shouldn't we expect to find particles consisting of the initial particle constituents?

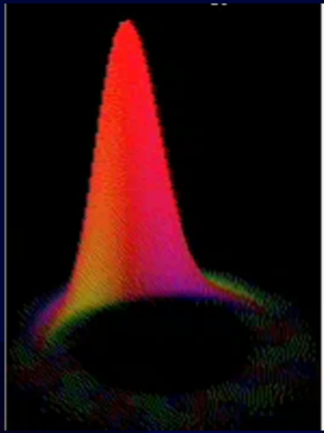
An element of chance in the microscopic world

$\Delta x \cdot \Delta p \sim h$

Werner Heisenberg



Classical model of atoms

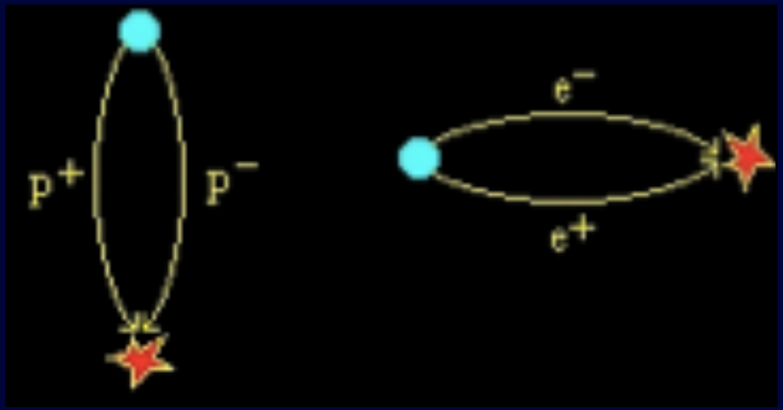


Quantum mechanical model of atoms

Quantum Vacuum

"Nothingness" is the most exciting medium in the cosmos!

Quantum fluctuations create and annihilate "virtual particles" in the vacuum



$\Delta t \cdot \Delta E \sim h$

At huge Particle Accelerators

virtual particles + energy → real particles

quantum vacuum

accelerator

production of new particles

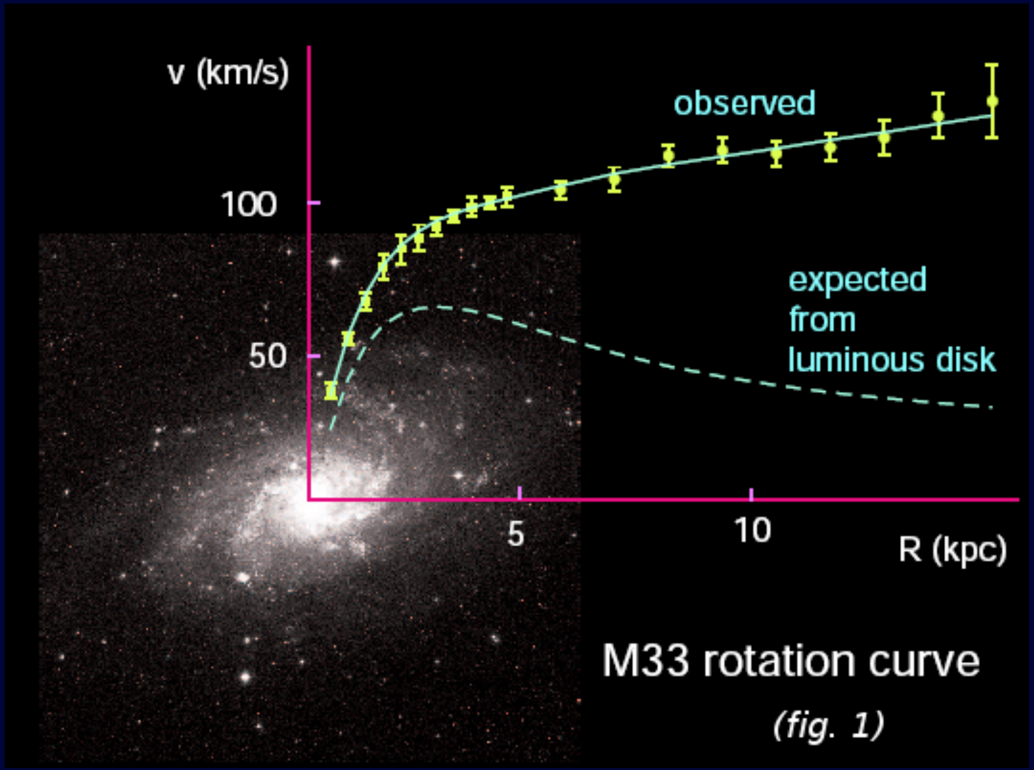
Quantum Fluctuations can produce the Higgs at the LHC

The Dark Universe

Fritz Zwicky

Vera Rubin

The rotational velocity of galaxies



There must be a lot of matter that we cannot see

Dark Matter ~ 85% of all the matter in the universe!

SUSY and the WIMP "Miracle"

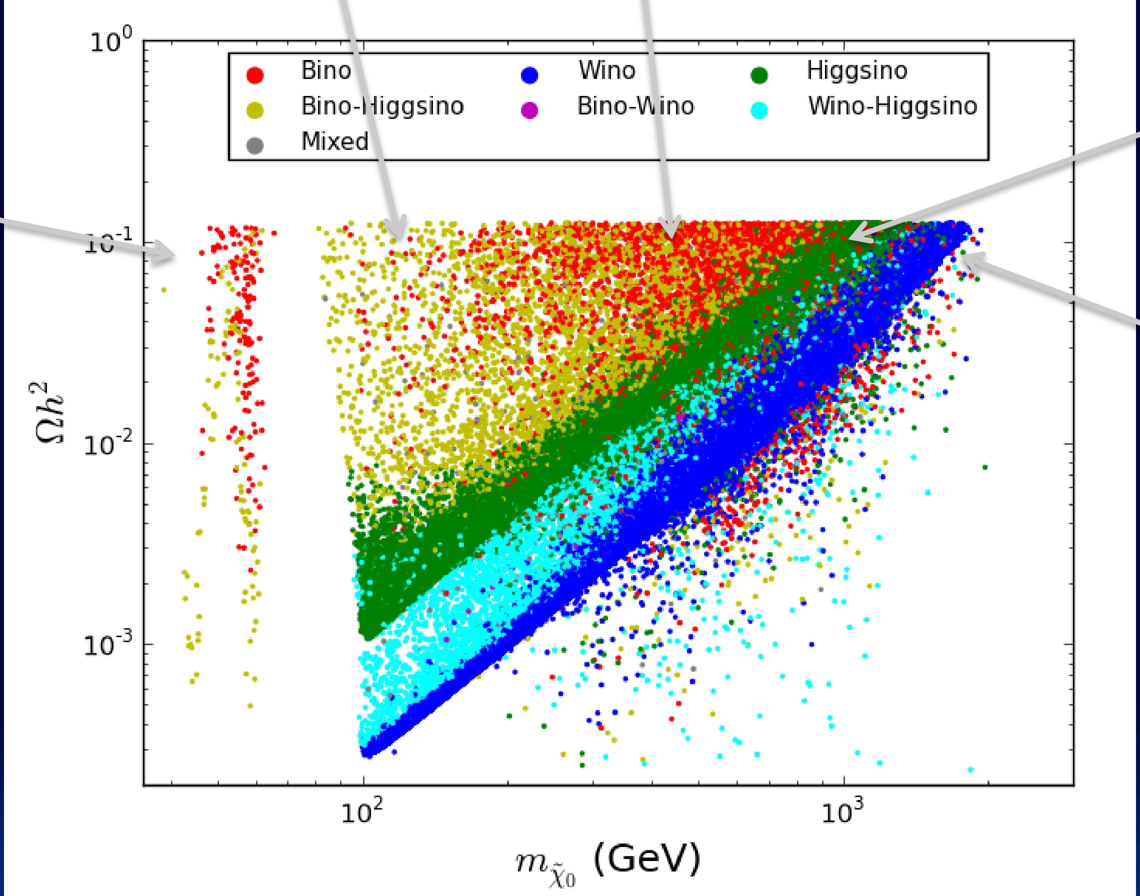
Bino-Higgsino mixture, closest case to the WIMP Miracle

Pure Bino needs co-annihilation with other quasi-degenerate superpartners

Bino-like that can annihilate through the h or Z "funnels"

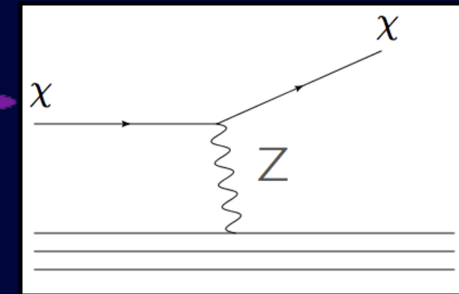
Higgsino, ~ 1.5 TeV

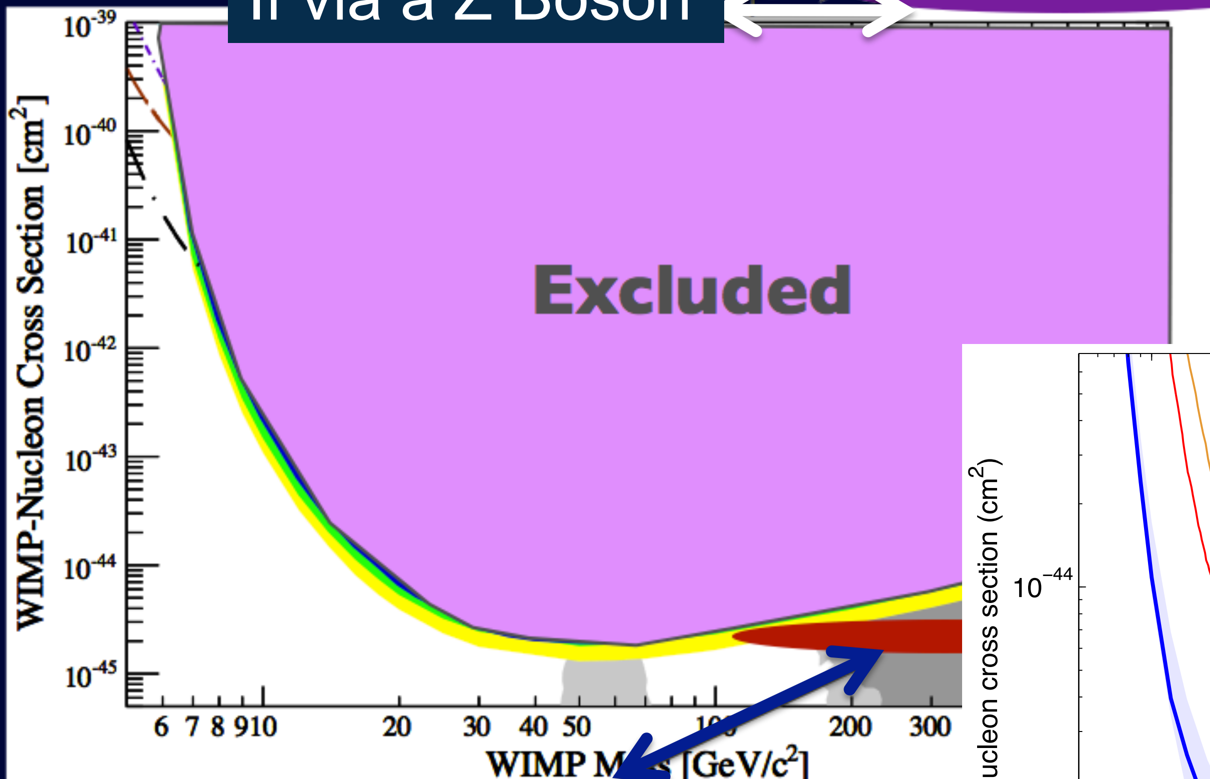
Wino, ~ 3 TeV

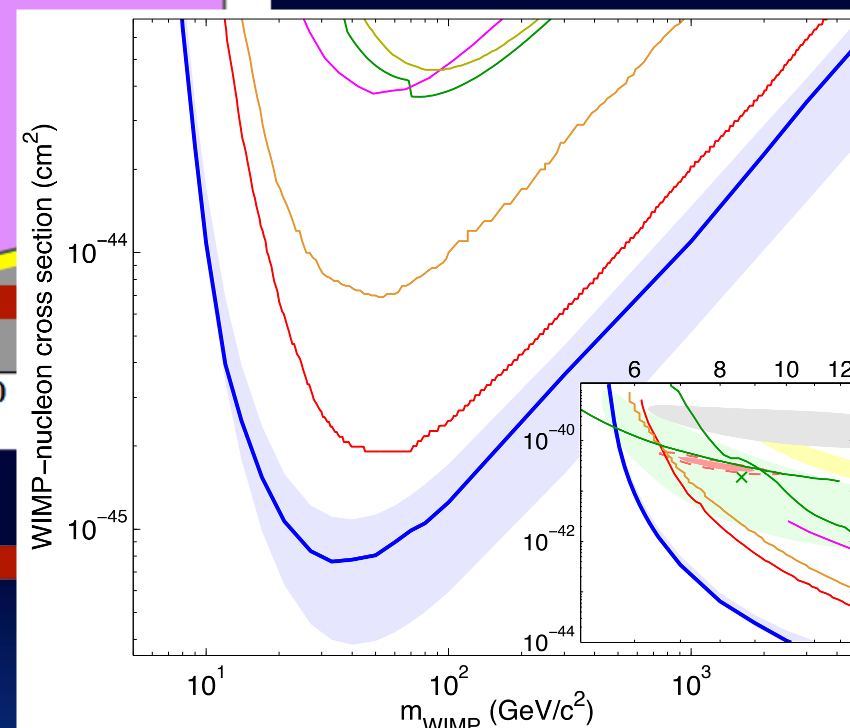


Starting to probe the Higgs Portal

If via a Z Boson







If via a 125 GeV Higgs

If via a 500 GeV Higgs